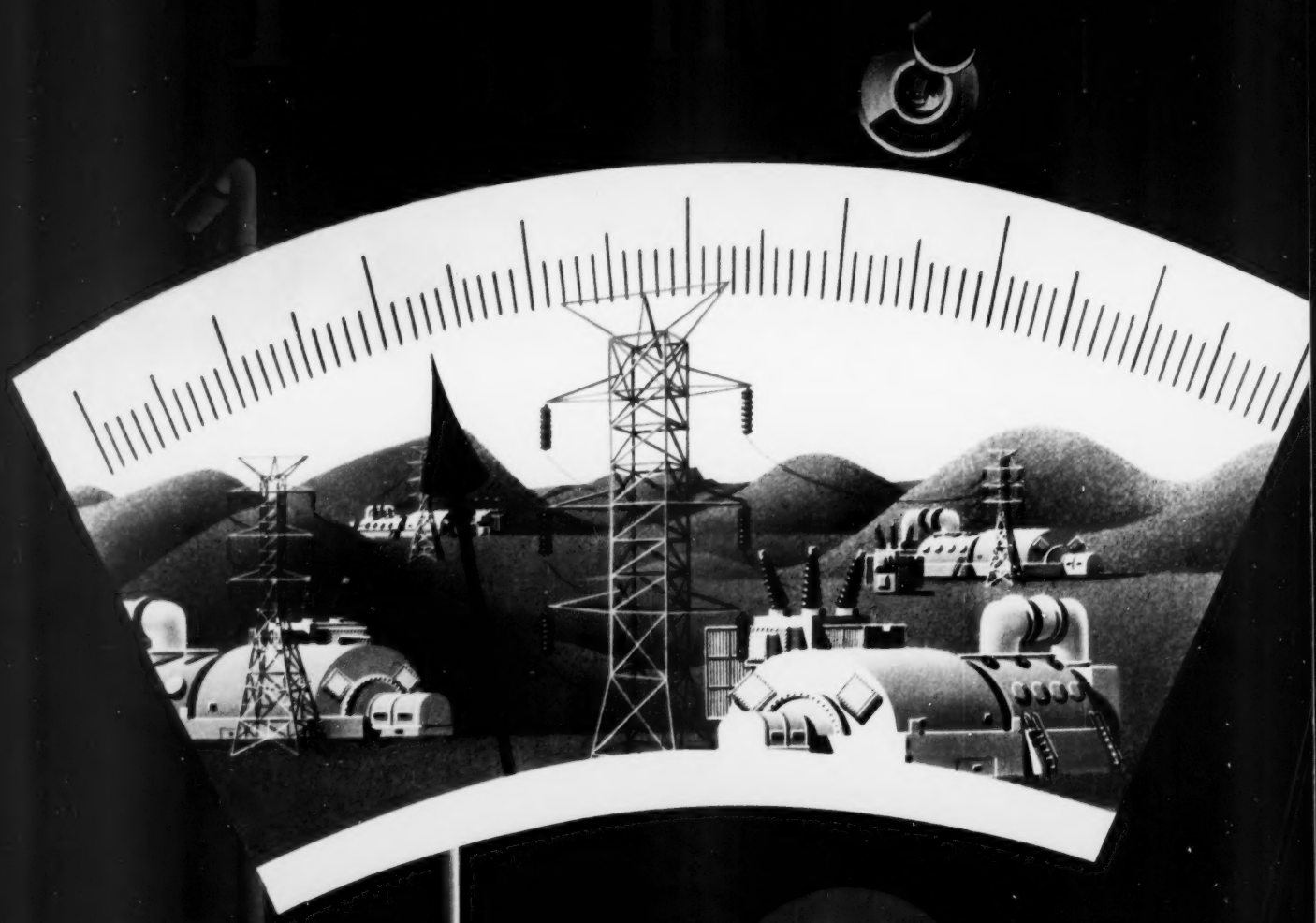
WESTINGHOUSE



NOVEMBER 1954

the dawning day of Computers

People with but a nodding acquaintance with computers and calculators are apt to consider them as somewhat awesome devices that produce near-miraculous results. Engineers who are on more intimate terms with the capabilities of these devices are more likely to consider them as but tools—albeit valuable ones—to help them solve their many problems. Actually these attitudes are not conflicting.

Without doubt the results produced by modern computers are amazing—and we have as yet hardly scratched the surface of their potentialities. One example: a few years ago a complicated blade-vibration problem necessitated a more or less trial-and-error solution, involving innumerable long calculations to arrive at the final answer. Two years of such calculation by an engineer equipped with a desk calculator and slide rule did not produce the answer. The same problem could now be done on a simple digital computer in about two weeks. On a more advanced computer in about four hours. And on the most modern computer in perhaps a minute!

From strictly an engineering standpoint, computers are used today for three general types of problems. First there are those involving long calculations that are impractical to solve by hand because of the vast amount of time involved and the number of variables—such as the blade-vibration problem. Second are those that are uneconomical to solve by manual methods; an example might be economic dispatch in a complex, rapidly growing system; while hand solutions could be made for every condition, each change in the system would necessitate new solutions. In such a situation a computer, easily adjusted to new conditions, would be the only economical solution. And the third category includes those that would be less economical by hand; for example, the duty cycle of a mine-hoist might take a day and a half by manual calculation, and but a few minutes or less by computer.

The variety of straight engineering problems that can be handled on computers is in itself staggering. Analog-type computers, for example, are especially valuable for transient problems; in one form or another they can solve most problems—mechanical, hydraulic, fluid flow, to name a few—that can be reduced to an electrical analog. This includes the myriad of regulating-system problems. The a-c and d-c calculating boards are essentially analog computers, in that an electrical system is set up in miniature; a complete power system, for example. Digital computers are more flexible, and are especially valuable where a great mass of data must be handled. In a broad sense they can handle any problem that can be represented by numbers, letters, or symbols. Performance calculations of apparatus, reduction of data to simplified form, light-distribution patterns, calculation of natural frequencies of mechanical systems, and heat-balance conditions are some of the many straightforward problems that can be solved.

But computers have broader implications than merely as over-sized desk calculators. Their use is immeasurably broader because of the supplementary devices that can be tied in. Information-storage devices, or "memories," sorting, and collating devices, for example. And without too much difficulty computers can be made to feed their results into control equipment, such as, for example, could be done with the economic-dispatch computer (see p. 194). Stretching this situation a little further, computers could control manufacturing operations, correlating flow of materials, operation of machines and the multitudinous other factors. They will undoubtedly play a leading role in the automatic factories of the future. Even whole networks of computers, controlling far-flung operations, are by no means inconceivable nor impractical.

The full potentiality of computers is a long way from being reached. The possibilities raised by the ease with which they can handle huge masses of information are tremendous. Take "safety factors" and margins for error incorporated in the design of most apparatus. Many of these exist simply because the task of calculating every conceivable occurrence has just been too formidable, and from a time standpoint, impractical. Quite possibly many safety factors could be drastically reduced by calculating actual conditions for a given situation.

Another of the many possibilities is in product design. An engineer must nearly always choose one or two different approaches to a given design, simply because he does not have the time involved to explore each and every possible solution. A computer can be set up to optimize all the engineering design factors and come up with one, two, or three of the best designs—from which the engineer could then make a final selection on the basis of some of the intangible factors, such as appearance.

Thus far, computer application has not yet caught up with computer potentialities. Part of the reason lies in the large amount of preliminary planning that must precede the application. Another factor is the tremendous rapidity with which digital computers have increased in power—a factor of ten each year for the last ten years, or a total of ten billion to one. There simply has not been time to build these latest machines on a large scale or to work out the applications. Nevertheless, the day of computers has dawned fast. More extensive use seems only a matter of expending the necessary time and effort. RWD

WESTINGHOUSE Engineer

VOLUME FOURTEEN NOVEMBER, 1954 NUMBER SIX

On the Side

The Cover—Among the many fields being invaded by computers is that of economic dispatch of electric power. This month's cover by Dick Marsh suggests the computer's role in this application.

• • •

A new 547-foot-long ore bridge for unloading iron ore from lake vessels and railway cars was recently put into operation by the McLouth Steel Corporation. Built by the Dravo Corporation and powered by Westinghouse electrical equipment, the new unloader will hoist at 300 feet per minute, carrying about 27 000 pounds of ore at each bite. In 41 seconds the new bridge completes one cycle—digging the ore, hoisting it, trolleying it across the bridge, dumping, rehoisting the bucket, and then returning for another load of iron ore.

• • •

As regular readers may have noticed, several changes have taken place in the editorial staff of the magazine.

C. A. Scarlott, former editor of the ENGINEER, has joined the Stanford Research Institute in Stanford, California, as Manager, Technical Information Services. Mr. Scarlott had been editor of the magazine since its initial issue in 1941, and prior to that was associated with the *Electric Journal*. R. W. Dodge becomes the new editor.

M. M. Matthews, who previously devoted part-time efforts to the magazine, has become assistant editor. Although a new name on the masthead, Mr. Matthews has frequently edited and authored articles for the magazine.

In This Issue

ECONOMIC LOAD DISPATCHING 194
E. L. Harder

A LONG LOOK AT LIGHT 201
Samuel G. Hibben

LIGHTNING ARRESTERS—STATION OR LINE TYPES? 206
Edward Beck

MATERIALS DEVELOPMENT FOR THE SUBMARINE THERMAL REACTOR 208
William A. Johnson

TRANSFORMER INSULATION POWER FACTOR—WHAT DOES IT MEAN? 213
E. C. Wentz

AN ENGINEERING PERSONALITY—CLARENCE LYNN 216

DEVELOPMENTS IN AXIAL-FLOW COMPRESSORS 218
A. I. Ponomareff

VIBRATION-SAFE TRANSONIC COMPRESSOR—VIA MODELS 222
D. D. Rosard

The following terms, which appear in this issue, are trademarks of the Westinghouse Electric Corporation and its subsidiaries: Autovalve, Magamp.

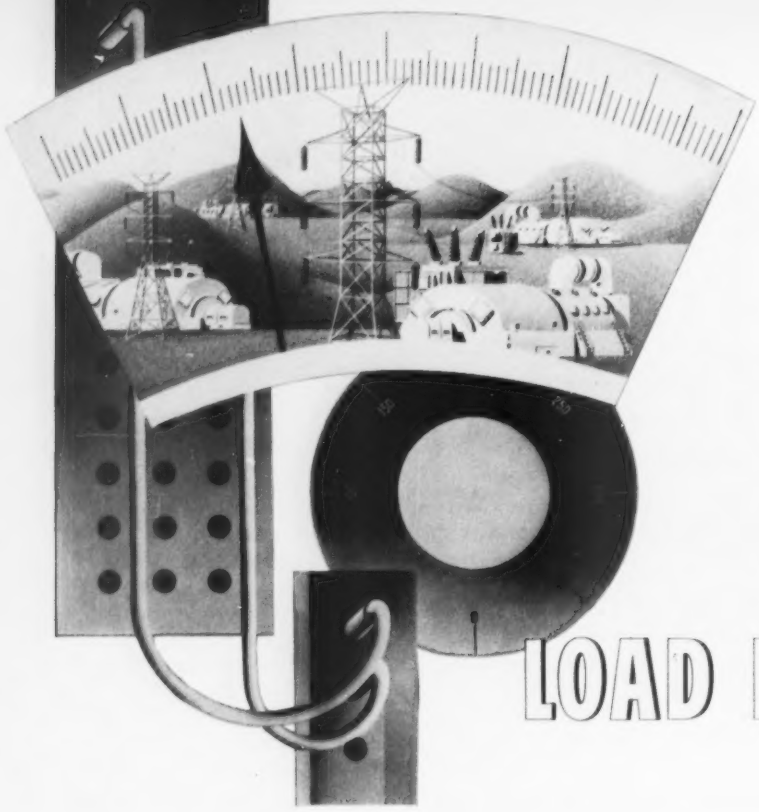
Editor ..... RICHARD W. DODGE
Assistant Editor ..... M. M. MATTHEWS
Layout and Production ... EMMA WEAVER
Editorial Advisors { A. C. MONTEITH, J. H. JEWELL, DALE MCFEATTERS

Published bimonthly (January, March, May, July, September, and November) by the Westinghouse Electric Corporation, Pittsburgh, Pa.

Subscriptions: Annual subscription price in the United States and possessions is $2.50; in Canada, $3.00; other countries, $3.00. Single copy, 50¢. Address all communications to *Westinghouse* ENGINEER, P. O. Box 2278, 401 Liberty Ave., Pittsburgh 30, Pa.

Indexing and Microfilm: *Westinghouse* ENGINEER contents are regularly indexed in Industrial Arts Index. Reproductions of the magazine by years are available on positive microfilm from University Microfilms, 313 N. First Street, Ann Arbor, Michigan.

THE WESTINGHOUSE ENGINEER IS PRINTED IN THE UNITED STATES BY THE LAKESIDE PRESS, CHICAGO, ILLINOIS



As power systems increase in size and complexity, dispatching power in the most economical fashion becomes more important —and vastly more difficult. New methods bid fair to solve this problem in predominantly steam electric systems.

E. L. HARDER
Director, Analytical Section, Westinghouse Electric Corporation, East Pittsburgh, Pa.

economic LOAD DISPATCHING

IN AN interconnected electric-power system, as long as load is less than available generation, some choice exists in the matter of how much of the load should be provided by each generating station, or how much should be purchased from or sold to adjacent companies over the various interconnecting lines. This decision is made by the system dispatcher, usually on economic grounds. Thus economic dispatch of generation has always been an objective on every power system.[1]

Transmission losses have always been recognized as an important factor in determining the economic dispatch. However, with a network of lines, transmission losses have been too difficult to determine hour by hour, so the determination of economic dispatch has been based on station costs, either ignoring transmission losses altogether or considering them in an approximate manner.

Recently methods have been developed for determining an

Loss Formula

The first step in obtaining a loss formula[2] is to determine a base case, centered in the range of system conditions for which it is to be applied. The loss formula thus derived will be exact for the base case, and less accurate as system conditions depart from base operation. Derivation of the loss formula is based on the following assumptions:

1—Generator-voltage magnitudes and angles are the same as for the base case.

2—The ratios of reactive-to-real power are the same as for the base case except for certain modifications.[8]

These two assumptions make it possible to convert generator power to current.

3—The total generator and tie-line current input to the system is assumed to divide among all the loads in the same vector ratio as for the base case.

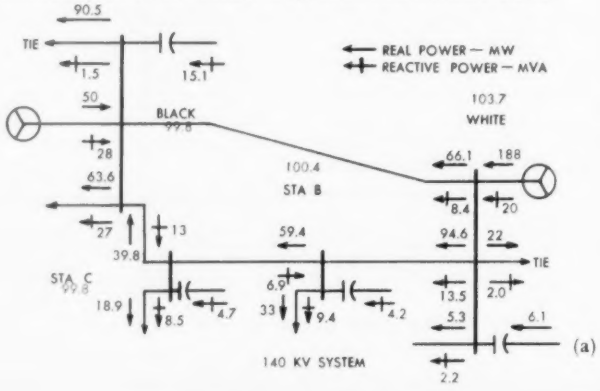
There are two other minor assumptions:

4—That all the line-charging capacity and synchronous condensers are lumped with the loads.

5—That the net transformation ratio around closed loops is assumed to be unity.

Utilizing these assumptions, the base case is set up on the network calculator. A simple system suitably labeled for a base case is shown in (a) at right. Quantities obtained from the calculator study can be grouped on two diagrams, load-flow data consisting of real and reactive power flow shown in (a), and vector data, components of voltage and current shown in diagram (b).

Network constants for the system are determined on the calculating board after the base case has been measured. They are obtained by dropping off all of the loads, grounding one of the principal buses (which is then known as the reference), connecting a generator to one of the other buses and measuring all of the voltage drops from the reference bus to



accurate transmission-loss formula,[7] which expresses losses in terms of the amount of power generated at each station. With this formula, transmission losses can be included in the determination of economic dispatch. The general principle is as follows: The cost of fuel input to a system to supply a given load is minimum when the incremental delivered-power cost is the same from every variable station. The delivered-power cost includes the incremental cost at the generating station plus the incremental cost of transmission losses. The equations stating that these costs are the same from every variable station are called the economic-dispatch equations, since they can be solved to determine the amount of power that must be generated at each station to meet this condition. These equations are solved for 15 or 20 values of load ranging from light to heavy and the resulting solutions plotted to show the correct dispatch for every value of system load.

Such a family of economic-dispatch curves must be based on fixed quantities; specific values for the fuel costs, availability of units, dispatch of power in the tie lines, and certain other considerations must be chosen. Consequently, a considerable number of curves must be plotted for different conditions, or means must be available for modifying them. Usually new curves must be made every six months or so, to reflect changing fuel costs and system conditions. Nevertheless, the savings are considerable, and easily justify the effort expended. Even more desirable, however, would be an economic-dispatch computer, located in the dispatcher's office, which could be kept continually up to date with system costs and availability of units; this not only would give a more accurate answer, but would obviate the frequent re-study of the problem. With such a computer, changes need be made only when major changes occur in the network, such as the building of a new transmission line. This requires a revision of the loss formula that must be set into the computer. Thus at the present stage of development, both precalculated curves and economic-dispatch computers have a definite place in the picture; both are based on the same theoretical considerations.

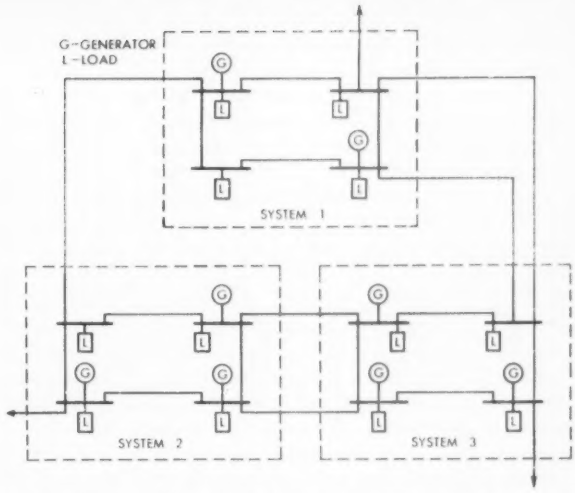


Fig. 1—Simplified diagram of three interconnected power systems.

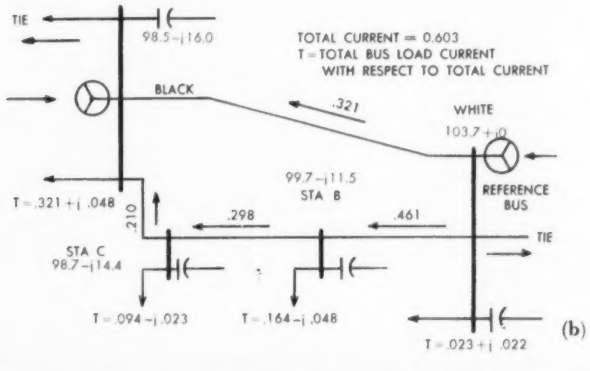
Dispatch and Loss Considerations

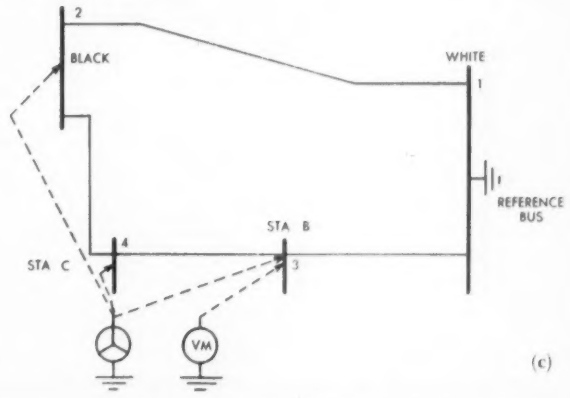
The problems of economic dispatching and loss evaluation can be visualized by reference to Fig. 1, which shows three interconnected systems. Assuming that system 1 is an independent operating company with ties to two of its neighbors, the information desired may be the economic dispatch of generation in system 1, with fixed power in the interconnections determined by contractural relationships. Or, the condition desired may be the operation of the three systems for greatest overall economy. In this case, for accounting purposes, it may be necessary to determine the actual savings in each system due to inter-system flows, so as to spread the savings equitably. Another example of the use of loss formulas arises in connection with the sale of power by one system to another. Suppose system 1 is selling power to system 2 and wishes to ascertain the transmission losses in its own system associated with this sale. These losses are then added to generating costs

the various buses. These drops per ampere of generator current are the network impedances. This is repeated except connecting the generator to a different bus each time. The board setup for this operation is shown in (c). When these network impedances—known as the self- and mutual-drop coefficients—have been obtained, they and the three frameworks (generator voltages, reactive-to-real power ratios, and load-current distribution) are processed by a turn-the-crank procedure[7] to develop the B constants for the loss formula. This is best accomplished by a digital computer, although for simpler systems it can be done by hand calculation or a desk calculator. The loss formula for a two-station system is:

$$L = B_{11}P_1^2 + 2B_{12}P_1P_2 + B_{22}P_2^2$$

In general, the formula contains a power-squared term for each generating station and a power-product term for each pair of stations.





to get the total cost at the interconnections. If some power flows through system 3 in getting from system 1 to system 2, the amount of associated losses may also have to be determined and accounted for in the inter-system transactions.

In numerous locations of the country today, several small groups of interconnected systems are joined to form large power pools. These pools are operated for greatest economy. Within each small system group, the problem of economic operation also arises. One arrangement for operating the larger pool is to have a single dispatcher who has available the incremental costs versus total generation for each of the parties. He then dispatches the next block of required generation to whichever party has the lowest incremental cost for that block. Such cost schedules are made up in advance and form the basis of the contract. Once having given a schedule, each company is obligated to supply power at that rate, regardless of changes that take place on its system. This is necessary because other companies base their action on this rate. However, each party is still free to effect any further economies within his system. To date transmission losses have been either neglected or approximated; however, various schemes are under consideration for taking them into account.

In other cases, several companies have combined to feed power to a large load involving considerable transmission of power through other systems. Workable agreements have been reached to share the cost of transmission losses. However, considerable development is necessary before losses can be completely and accurately taken into account.

Loss Formulas

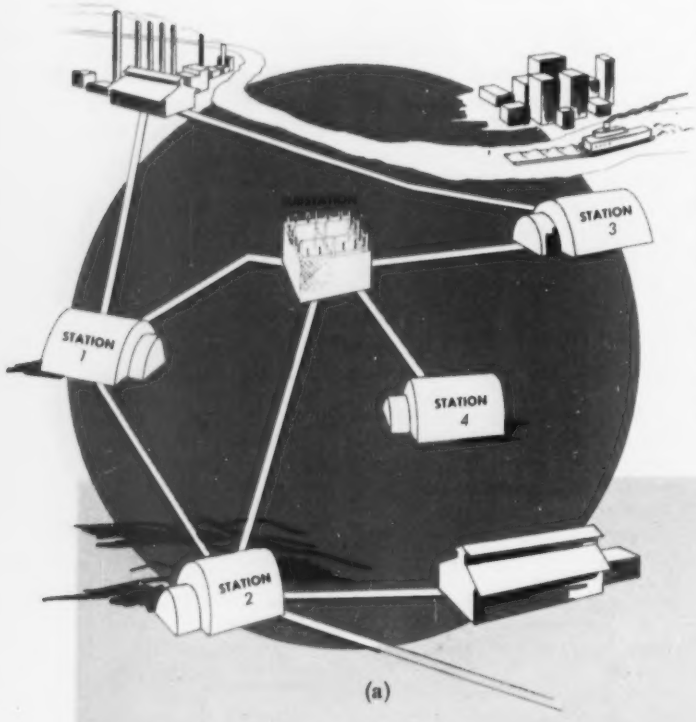
As has been mentioned, economic dispatching taking into account station costs has been in common use for many years; the new feature is improved methods for considering transmission losses. Consider now the loss formulas.

Power-system losses can be roughly divided into two categories—fixed and variable. For the transmission system, the transformer-exciting losses represent the principal fixed loss, whereas losses in the series resistance of transmission lines and transformers are variable with load current. These are the I^2R losses. Only variable losses are of interest in economic dispatching. Since station cost is a function of generated power, the cost of transmission losses must also be expressed in terms of generated power so that it can be added to the station costs. This is the principal dilemma of obtaining a loss formula. It necessitates a suitable set of assumptions such that, given the generated power at each station, the current in every transmission line is fixed, and therefore losses are fixed. This requires setting up a framework for the conversion of generator powers to line currents, and hence to losses. Such a framework is based on a typical load-flow condition, usually represented on an a-c calculating board. This typical flow condition is well centered in the expected field of use of the loss formula. The loss formula is discussed on p. 194.

The transmission-loss formula is useful for a great many purposes. It can be used to determine the losses associated with sale of power, to evaluate various system plans, to determine the system losses under any particular condition of loading or generation. However, one of its most important uses is that of calculating transmission losses in order to determine the most economic dispatch.

Economic-Dispatch Equations

As mentioned, the system fuel cost to supply a given load is minimum when the incremental delivered-power cost is the



(a)

(b)

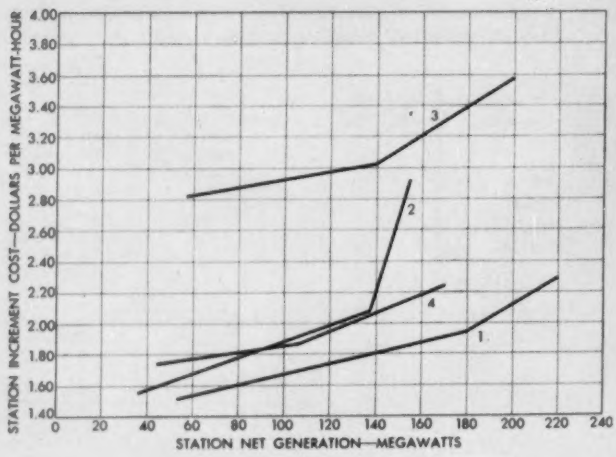


Fig. 2—A hypothetical four-station system illustrates the application of economic load-dispatching curves (a). The *B* constants obtained in the derived loss formula for the system and station incremental-cost curves (b) provide the necessary coefficients for the economic-dispatch equations. The equations, when solved for several values of average incremental delivered-power cost (λ), yield a family of economic-dispatch curves (c), illustrative of studies made on the Westinghouse a-c calculator and digital computer.

same from every variable station. This is logical, since if the incremental delivered-power costs were different, total fuel cost could obviously be lowered by dropping some power from a station having a high incremental delivered-power cost and raising correspondingly a station with a lower cost. There are, however, a few refinements that should be mentioned. The incremental delivered-power cost is the sum of the production cost at the station, mainly fuel cost, and the incremental cost of transmission losses. The latter cost depends both on the amount of the incremental transmission loss and on the price charged for it. Some question has arisen about whether incremental transmission losses should be charged at the station cost, the delivered cost, or some other average value. However, it has been proved that the minimum fuel input to the system is actually obtained when delivered costs are the same, with the incremental transmission losses charged at the incremental delivered-power cost.

The term incremental delivered-power cost is usually applied to the average incremental cost for the entire system load. However, taken over the system as a whole, the incremental cost varies from point to point; and, in general, for the economic-dispatch condition, power flows from the low-cost stations toward the high-cost stations in exactly the right amount, so that the cost of the losses entailed in the interchange flow exactly equals the differences in incremental station costs.

Reference has also been made to variable stations. Naturally, some stations may be fully loaded and operating at an upper limit at high system loads. When they reach the limit, the equations for these stations drop out of the economic-dispatch equations, since above this point it is only feasible to make the delivered cost the same among the stations that are still "variable." Likewise, certain stations may have a lower limit for area protection or from an operating consideration, and these units also are not regarded as variable units at these particular loads. Thus the physical picture of a system operating in economic dispatch is that certain units may be operating at fixed loads and others at variable loads, but the incremental delivered-power costs from all variable units are the same.

Other interesting tests give a good physical picture of the system under economic dispatch. For example, if an additional load is connected at any point in the system, power to supply it can be generated at any of the variable stations at the same cost. This applies only to a very small increment and is explained by the fact that the flows in the system are such as to equalize the costs from all of the variable stations to each other, or to any other point in the system. Another test is that of reducing the power slightly at one variable station and increasing another station sufficiently so that the load is unaltered. This also does not change the cost. Presumably, more power would be required if this load were picked up at a lower-cost station because the losses from that station would be greater. However, the costs are the same.

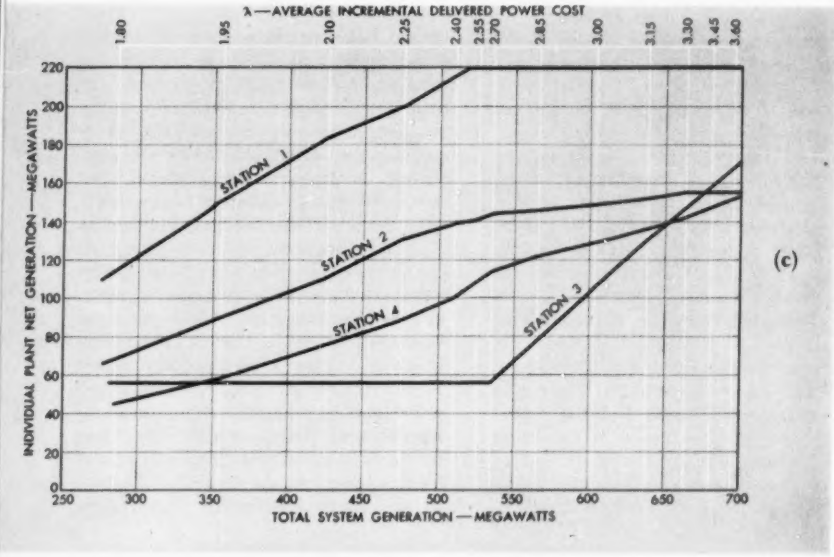
The equations that describe this equality of delivered power costs are as follows:

$$\begin{bmatrix}\text{Station Incremental}\\ \text{Production Cost}\end{bmatrix} + \lambda \begin{bmatrix}\text{Incremental Transmission Loss}\\ \text{Associated with that Station}\end{bmatrix} = \lambda$$

where λ is the incremental cost of delivered power. For a two-station system:

$$a_1P_1 + b_1 + \lambda[2B_{11}P_1 + 2B_{12}P_2] = \lambda$$
$$a_2P_2 + b_2 + \lambda[2B_{12}P_1 + 2B_{22}P_2] = \lambda$$

These equations apply for a two-station system in which both stations are variable and are supplying the powers P_1 and P_2, respectively, and where the B constants are the coefficients of the loss formula described previously. Average incremental delivered-power cost is represented by λ; note that the incremental transmission loss associated with each station is multiplied by λ. Note also that station cost is indicated by a straight line with a slope a and intercept b (see formula). In the case of ten variable stations, there would, of course, be ten such equations instead of two and the incremental loss (for each station) would contain ten terms, plus a term for each fixed station or tie. This is because the incremental loss associated with the delivery of power from a particular station



(c)

Hydro Considerations

Hydroelectric power presents a much different dispatch problem. The methods described in this article apply to systems composed mainly of steam-electric generation, in which the dispatch of hydro power, if present, is determined by other considerations. Often the hydro generation is determined by the run of the river, in which case it can be considered fixed by this condition and the dispatch of the steam portions determined as outlined. In the short-term hydro problem, a certain amount of water is assumed to be available for use during a given period of time; a further assumption is that the load-time curve for this period is known. The best dispatch of steam and hydro power during this period is the desired information. Methods have been developed for attacking this problem.[9] In the long-term problem for a system that is predominantly hydro, the uncertainties due to load and water predictions are sufficient that the inclusion of transmission-loss considerations is not worth while. However, in actual operation, once the hydro-power dispatch has been determined by these long-range considerations, the most economic dispatch of any steam generation can be determined by the means given here or by a solution of the short-term hydro problem.

depends on how much that station and each other station or tie in the system is supplying at the time. These equations are known as the *economic-dispatch equations*. Their solution for a particular value of λ yields a set of station powers, P_1 and P_2, which constitute the economic dispatch for some system load equal to their sum. Thus by selecting 15 or 20 values of λ covering the range of delivered-power costs of interest on the particular system, the equations can be solved a sufficient number of times to obtain a complete family of economic-dispatch curves (Fig. 2c). Each solution for a value of λ yields one cross-section set of points on this family of curves.

This work is normally carried out on a digital computer, which solves the equations by an iteration process (Table I). While the details of solution are not of particular interest here, the iteration method does require only one third the time of a classical solution, and makes possible a solution for any reasonable number of generating stations with considerable ease. In fact, the entire solution for the economic-dispatch curves for a large utility, including a number of additional checks, required less than two days. The computer can be equally well programmed to solve the economic-dispatch equations for desired values of total generation or for a particular generation at one station.

The economic-dispatch curves in Fig. 2c are known as precalculated curves for obvious reasons. They are necessarily based on certain fixed conditions of the system. For example, a fixed network is assumed. The curves are also based on zero power in all interconnections with neighboring systems and on full availability of units in all generating stations (i.e., no units out of service for maintenance at the time). Fixed fuel cost at each of the various stations is also assumed. Also, the economic dispatch so obtained involves specific flows in the various transmission lines of the systems; it is entirely possible that some conditions represented are not feasible due to the limitations of transmission facilities or equipment. More likely, however, system design and construction, except for extreme emergency conditions, permits economic operation.

The extent to which these conditions present a serious problem in the use of precalculated dispatch curves varies widely with the nature and extent of the system. For example, the economic dispatch of generation indicated by curves that were obtained for one large utility company were found to apply closely for the following five conditions of service, which differ considerably from those for which the curves were taken:

1—For power flow in the tie lines resulting in swings in excess of line capacity east or west over the system.

2—For large economic interchange transfer to a neighboring system, in place of supplying that amount to the system load.

3—For a major unit out of service at a generating station, dispatching the deficit like additional system load.

4—A change in fuel cost at a particular station can be interpreted also as a deficit of power at the previous cost and the deficit dispatched as in 3 above.

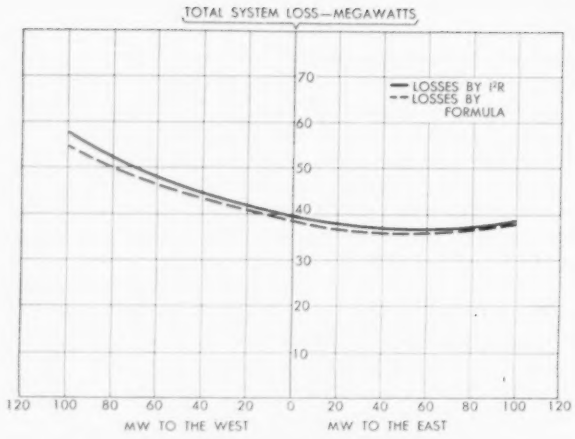


Fig. 3—Variation of system loss with transfer power; note the close relationship between the curve obtained by formula and that calculated by I²R methods.

Computer Solution of Four Simple Problems

Consider four general problems to be solved by the computer. The illustration at right shows diagrammatically the components of an economic-dispatch computer. First, let it be required to determine the dispatch for a particular total generation. Assume that station-cost curves have been set by means of the plug board (see diagram) and that the transmission-loss coefficients pertaining to the transmission system have also been set into the computer. With the selector switch in the compute position, the total-generation dial is set at the desired generation value; the several station-power indicators then move under the control of the computer circuits to positions that indicate the proper amount of power to be dispatched from each station. The meter at the top indicates the average delivered-power cost and the second meter shows the incremental cost at any station or tie line for this condition, by depressing the corresponding station-cost button. As a variation of this problem, if the cost at station 1 is increased ten percent above that for which the station-cost curves were calculated, the small dial under the station dial would be moved up to 1.1 and the computer would immediately show the correct dispatch for this condition.

Second, suppose the system consists of two generators and one tie line, and 50 mw of scheduled power is coming in over the tie line; the economic dispatch of the system generation under this condition is desired for a particular total generation plus tie power. The third station representing the fixed tie would be thrown to the fixed position (toggle switch), and set on 50 mw. The total-generation dial is again set for the desired total and the two station dials position to show the correct power dispatch.

Third, assume that the incremental cost is desired for a block of 50 mw brought in over the tie line. The incremental value of this power to the system changes as the amount is increased from zero to 50 mw, and the cost of interest is the average incremental cost. This can be obtained accurately by the computer, or approximated by adjusting the tie-power setting to show half of the power increase, and reading directly the incremental value at this point. This is the average incremental cost for the full block. It can be determined either with the additional power used to substitute for some of the running generation, or considering taking on this additional block to feed the next block of load on the system. The computer gives the answer to either question.

5—Since the dispatch of sale power can be taken the same as the dispatch of system load, it can be considered known, and therefore the cost of power at the interconnection can be expressed in terms of the incremental delivered-power cost, λ, and the sale power. This information is highly advantageous to the dispatcher.

(On other systems that spread over a larger area and involve relatively greater resistances between several load-generation areas, these approximations may not work out with acceptable accuracy; in this case a larger number of economic-dispatch curves is necessary to cover the full range of conditions.)

Extensive changes in the system, such as the building of a new transmission line or generating station, require a new loss formula, whereas changes in fuel costs or system operating conditions may require additional economic-dispatch curves using the previous loss formula.

On some systems these changes are sufficiently infrequent as to make precalculated dispatch curves entirely feasible. Also, on some systems the number of required precalculated families of curves is extremely small. For example, one family of curves was considered adequate for one large mid-western system that supplies power to more than an entire state. On other systems, fuel costs may change at frequent intervals due to the availability or changing costs of gas. Also system flows may be changed radically due to the presence or absence of hydroelectric power, which calls for radically different dispatch of the steam generation.

Further comment is also required at this point on the load current. For many systems, loads can be considered almost homogeneous, that is, varying together as the system changes from light load to heavy load. This relationship has been found surprisingly close on several systems studied. However, on other systems large steel-mill or mining loads may vary widely due to industrial conditions, with little relationship to other loads. With respect to these, there appear two possibilities. They can, of course, be treated as generating stations or tie lines; in other words, to determine the dispatch, the steel-mill or mining load would be set and the generation

TABLE I—EXAMPLE OF SUCCESSIVE APPROXIMATIONS TO THE ECONOMIC DISPATCH, MW

Power Source	First Approximation	Second Approximation	Third Approximation	Exact Solution
Station A	38.42	40.128	40.437	40.422
Station B	136.09	135.707	135.769	135.758
Station C	206.24	208.466	208.336	208.378
Station D	45.78	56.753	56.889	57.044
Station E	73.76	78.042	78.368	78.373

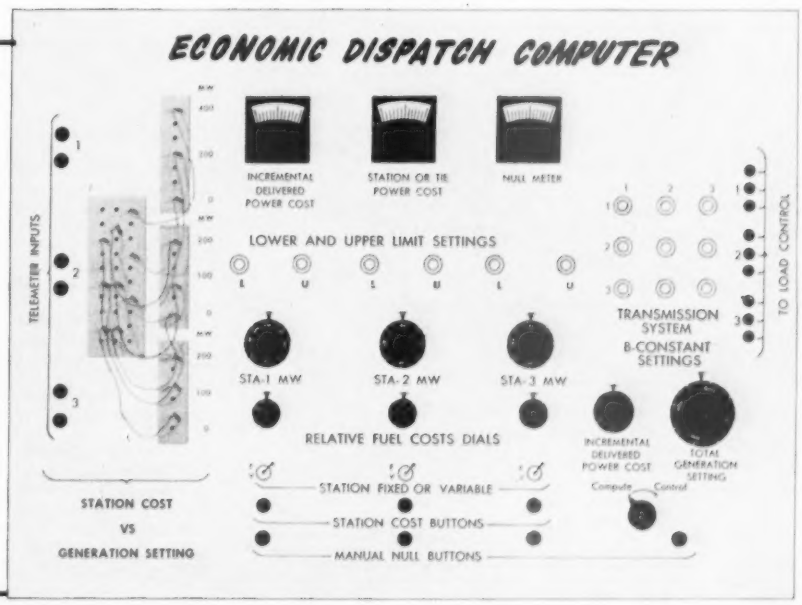
dispatch determined for several different conditions of this load. This obviously increases the number of precalculated curves necessary to describe a system adequately.

The second possibility, which is only workable on certain systems, is to ascertain whether the dispatch of the particular mining or mill load is the same as for the general load, even though they do not vary together. For example, in one power company the most economic dispatch for sale power over one of the interconnections was the same as the dispatch of a similar amount of power to the general system load within 0.1 mw at any generating station. Even had the differences been several megawatts, this would still be within the accuracy of the telemetering equipment used for dispatching, so the differences could be considered unimportant. If this condition can be shown to exist in any particular case, then the non-homogeneous load can be dispatched the same as the rest of the system load. Otherwise such loads constitute a problem, one solution to which is some form of economic-dispatch computer.

Economic-Dispatch Computers

Several conditions may necessitate an objectionable number of precalculated dispatch curves to cover adequately the range of operating conditions encountered in a particular system. A large number of curves is objectionable for two reasons: First, the operator never quite knows which to use and is likely to be confused by trying to interpolate between non-applicable curves; and second, an excessive number must be recalculated for each major change in fuel costs or each new construction on the system.

Fourth, suppose the computer is to be cut into automatic control of the system. The telemetered indications of generation at each station are brought into the computer, and the control switch is thrown into the "control" position, which makes certain changes in the computing circuits. The station indicators then show the actual generation at each station instead of the economic dispatch; contact circuits are set up to route the raising pulses of the load-control system to stations having low incremental-power cost, and the lowering pulses to stations having high incremental delivered-power cost. The pulses can be originated by any automatic load-control system. The computer thus acts as the sensing element and does not interfere with the normal functioning of the load-control system in assigning frequency and swing-load contributions.



Loss Formulas for Simple Systems

For many simpler systems that can be represented as various stations tied to a single main interconnecting trunk, a simplified form of loss calculation is described in reference 6. In this simplification, the power flows are treated as substantially in-phase, and percent current is assumed to be the same as percent power. This simplification, plus the reduction of the network by transformations to a single main interconnector, makes possible the calculation of losses for any dispatch by a simple sum of products, without any network solution. Thus various dispatches can be compared readily either to determine the economic dispatch, or to ascertain the value of carrying the work to a more elaborate stage. Furthermore, on systems in which the network is being changed rapidly, loss and dispatch calculations by this means may be more feasible than by the complete methods described in this article.

Factors necessitating numerous precalculated-curve families include: (1) alternate fuel-cost possibilities at a station; (2) taking units out for maintenance; (3) system too extensive to utilize the approximations involved in a single family of dispatch curves; (4) system growing rapidly, involving new construction. This necessitates only one change in the computer for a change in the system, but may require recalculation of a great many precalculated curves for some systems; (5) different scheduled flows in tie lines; (6) different economic-interchange conditions; (7) dispatches to obtain cost of power at interconnections; (8) dispatch curves for system planning; (9) curves for other temporary or emergency conditions; and (10) various combinations of boilers and machines used in a station.

These conditions create a desire for a computing device that can be used directly in the dispatching office to show the correct dispatch at all times. This device should preferably incorporate provision for convenient alteration as the loss formula changes due to construction of transmission lines, etc. Changes in fuel costs should be easily represented without changing the entire thermal-efficiency curve of the station. Highly desirable would be a direct indication of the cost of power at interconnections, since the savings due to more effective operation of economic interchange based on more accurate knowledge of costs can easily approach the other more obvious savings of economic dispatching. The device should show the average delivered-power cost and the cost at various generating stations and ties. In some cases, it would be desirable to tie the computer to the automatic load control of the system, the computer acting as the sensing element, detecting and correcting for deviations from economic dispatch.

A number of approaches to the economic-dispatch computer are evident. In one development[10] a transmission-loss penalty-factor computer is used to compute the penalty-factor settings for an economic-dispatch slide rule. This is obviously intended simply to inform the operator and not for connection to an automatic control. In another approach, a computer determines incremental power cost and the system itself is adjusted until these costs are equal.[11] In still another arrangement, under development by Westinghouse (in conjunction with the West Penn Electric Company), both station costs and loss-formula coefficients are fed into the computer; the computer can then be set for any desired total generation and automatically adjusts itself to show the correct dispatch for this condition. Upper and lower limits for the various generators, together with the correct station-cost characteristics applicable at the time, are set into the computer. This same computer can be cut in as the sensing element of an automatic control. The controls and indications that would be present on such a computer for three stations are shown on p. 199, along with four simple problems.

Acknowledgment is made for the substantial assistance of the following groups in carrying out the studies and developments reported in this article: Commonwealth Associates; Consumers Power Company; Ohio Edison Company; Pennsylvania Power Company; West Penn Electric Company; staffs of the a-c network calculators at Purdue, Illinois Tech; and the Electric Utility and Analytical Sections of Westinghouse.

Conclusion

Savings due to inclusion of transmission losses in the economic dispatch of generation have been estimated upwards of $50 000 per year per thousand megawatts of generation, as compared with the limited consideration of transmission losses that can be given without the more refined calculations. Further attractive savings are afforded by precise information on the value of power at interconnections, which will make economic interchange feasible to a much greater extent. The computer also offers simplification in the dispatcher's problem, which has been growing steadily more complicated and would become more so with the closer and more integrated operation of systems. The computer also offers the opportunity for predetermining generation schedules and costs for use of pool operations. It determines the savings due to economy interchange and pool operations, as needed in accounting to share the savings between the parties involved, and provides for studying in advance the efficient handling of expected load changes.

The precalculated curves are already in use on a number of systems and are affording substantial savings. Both the precalculated curves and economic-dispatch computers will undoubtedly find wide and profitable use in the electrical industry, with the trend naturally being toward computers as these are developed and become more efficient. Several forms of economic-dispatch computers for direct use in the dispatching office are contemplated.

REFERENCES

1—"Economic Loading of Steam Power Plants and Electric Systems," by M. J. Steinberg and J. H. Smith, McGraw-Hill Book Company, Inc., 1935.

2—"Intra-System Transmission Losses," by E. E. George, *AIEE Transactions*, 1943, p. 153.

3—"Coordination of Fuel Cost and Transmission Loss by the Use of the Network Analyzer to Determine Plant Loading Schedules," by E. E. George, H. W. Page, and J. B. Ward, *AIEE Transactions*, 1949.

4—"Effect of Transmission Losses on the Optimum Plant Loading Schedule of the West Penn Electric Company," by P. O. Bobo, M.S. Thesis, University of Pittsburgh, 1951.

5—"Evaluation of Methods of Coordinating the Incremental Fuel Costs and Incremental Transmission Losses," by L. K. Kirchmayer and G. W. Stagg, *AIEE Transactions*, 1952.

6—"Loss Evaluation—I, Losses Associated with Sale Power, In-Phase Method," by D. C. Harker, W. E. Jacobs, R. W. Ferguson, and E. L. Harder, AIEE 54–66, 1954.

7—"Loss Evaluation—II, Current- and Power-Form Loss Formulas," by E. L. Harder, R. W. Ferguson, W. E. Jacobs, and D. C. Harker, AIEE 54–67, 1954.

8—"Loss Evaluation—III, Economic Dispatch Studies," by R. H. Travers, D. C. Harker, R. W. Long, and E. L. Harder, AIEE 54–224, 1954.

9—"Short Range Economic Operation of a Combined Thermal and Hydroelectric Power System," by L. K. Kirchmayer, W. G. Chandler, and P. L. Dandeno, *AIEE Transactions*, 1953, p. 1057–65.

10—"A Transmission-Loss Penalty Factor Computer," by C. A. Imburgia, G. W. Stagg, and L. K. Kirchmayer, AIEE 54–68, 1954.

11—"Central Power Coordination Control of the Southern Company System," by E. D. Early, Southeastern Electric Exchange, October 1, 1953.

A Long Look at Light

After three fourths of a century of electric lighting, a reappraisal of accomplishments and possibilities is in order. Significantly, lamp engineers expect to see greatly increased use of man-made lighting, as well as new and improved sources to provide it.

SAMUEL G. HIBBEN, *Lamp Division, Westinghouse Electric Corporation, Bloomfield, New Jersey*

IF WE could really comprehend the exact nature of light, perhaps most of the mysteries that veil its future production would sooner be solved. If we could clearly grasp the definition of "light" as some species of lateral wave-motion in hypothetical ether or nothingness, weightless yet indicating mass or substance; unlike the wind, forceless, yet blowing the comet's tail by sunlight like smoke from a factory chimney —then perhaps its making would seem crisply definite!

Acting at one moment like the fastest moving of all possible vibrations—at another, like bundles or quanta, or dust clouds of particles—how can we come to grips with such an ephemeral, yet tangible wraith? Aladdin had it easy. He knew what would happen when he handled a lamp. But do we understand all the whys and wherefores when we operate one? Or when we build and burn a thousand varieties?

Can we define electricity as "crystallized light"? When sunshine, falling upon a square yard of photosensitive cells of silicon-boron "solar battery" (or upon cadmium-sulphide crystals), can continuously generate some 50 watts of electric power; and when, conversely, one watt of electricity, vibrating through a condenser-like electroluminescent plate, can generate perhaps 5 to 15 lumens of yellow-green light, surely this brotherhood is close! Surely this phenomenon incites more than casual curiosity. And if we might know the significant capabilities of radiant energy, especially upon animal and vegetable life, would not usage of light double and redouble? How much does the world need? And for what?

Light is versatile beyond belief! It develops the dyes in fabrics and then tests them for fastness. It produces fertilizer, blueprints, photographs, and uranium for atomic bombs.

It strengthens the bones through body metabolism of lime and phosphorus, or it kills the germs of disease and the spores of spoilage. Light can tenderize meat or harden plastics. It tans the skin but whitens linens, straw or cotton cloth. Light destroys obnoxious odors or explodes gases. Without it we would have no photosynthesis, no vegetation, and—no life.*

***In the photo above,* blocks represent relative efficiencies of each lamp. Left to right: 1000-watt incandescent, 100-watt incandescent, 400-watt mercury, 1000-watt fluorescent mercury, 10 000-lumen sodium, 40-watt fluorescent, fluorescent Slimline, electroluminescent plate, tellurium vapor, cold-cathode luminous tube.**

*A basic "equation of life," or of forming organic molecules is: 264 grams of carbon dioxide, plus 108 grams of water, plus about 700 000 calories of sunlight yield 180 grams of sugar and 192 grams of oxygen.

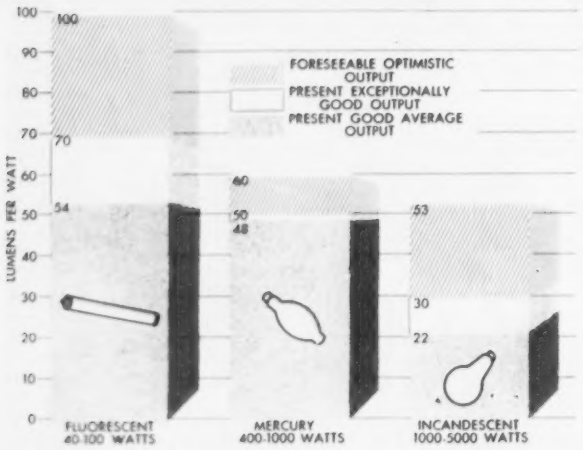


Fig. 1—This graph shows the present efficiencies and the future possibilities of fluorescent, mercury, and incandescent lamps.

It brings us 90 percent of all our knowledge, even from outermost depths of astronomical space, and it travels faster than any messenger boy we shall ever know. The constant wavelength of one color of light is our basic standard of length, and myriads of its wavelengths make our lives gay with unlimited colors.

Will better light sources increase man's use of artificial light? And to what end, or plateau? During only about two decades have we had reasonable economical means of generating such quantities of agreeable light as to lift its use from a dire necessity to the level of a healthy, pleasurable adjunct of good living. Compressed into the recent decades have been most of the commercial uses of light, over and above the original one of vision. So the science is brightly new. It merits frequent inspection!

Now during the Diamond Jubilee Anniversary, when three quarters of a century of experience and development have established a pattern—albeit a dynamic, not a static one—for electric-light sources and lighting applications, it is timely to take a long look at lighting, particularly at the means of producing tomorrow's radiant energy for vision.

It is important to reappraise the near future of this industry, because the incandescent lamp that Edison developed in 1879, regardless of how well its descendants have served humanity these 75 years, has nevertheless reached very close to the ceiling of its possibilities in efficiency, quality, and low cost of production. Because, also, the lighting years that complete the century are certain to encompass more progressive—yes, more radical and astonishing advances—than any other like period in human history!

True, the incandescent lamp still numerically represents by far the greatest volume of all illuminants, with its annual consumption of some 13 per capita and average size of 83 watts, but more and more during this past decade research engineers have turned to other and radically different light sources, because they see in today's developments and tomorrow's promises some very astonishing changes that bid fair to revolutionize the generation and the application of light. Already more lumen-hours of artificial light are generated by fluorescent, mercury, and similar vapor lamps, than by the incandescent-filament lamps.

Today's appraisal begins with the question of goals, because no generation of radiant energy is a matter of random development. The modern lighting scientist in particular directs his research activities toward a very specific achievement, for, unlike the times of Edison, a light source today must take into account a particular field of application; the parameters of production cost; a method of wiring with its details of voltage, frequency, and distribution; its foreseeable growth in efficiency; its color; its operation at variable temperatures; and a host of complicated factors. Today's lighting engineer is not a man . . .

> *"With a closed mind, aloof, too proud to know*
> *Anything very well—a worker who*
> *Always seems going, has no place to go."*

In achieving and promoting vision, probably the characteristic or goal of "luminous efficiency" is axiomatically the dominating one in any typical illuminant. More lumens from fewer watts means less heat discomfort, and usually best economy. A comprehensive look at light will, nevertheless, disclose the fact that luminous efficiency, although actually fundamental, is only one measure of the qualities of a good light source. Consider the list of approximate basic efficiencies in Table I.

How efficiently can we generate ordinary light? Edison's first lamps in 1880 had an efficiency of 1.7 lumens per watt.* Today's commercial illuminants range as high as 50 to 70 lumens per watt, an increase of at least 35-fold. However, if all of the electrical input to a theoretical light source could be converted to yellow-green light having maximum effect on the human retina, an efficiency of some 680 lumens per watt could be expected. If we elect to generate "white light" closely approximating average sunlight, this figure would be about 252 lumens per watt. Taking the latter efficiency as a goal, consider the efficiencies of ten typical light sources of today's production (Table II).

Thus far we have come in 75 years—or in hundreds of thousands of years of man's history, for that matter. We are about one quarter of the way toward the utmost efficiency.

*Rated 16 c.p., "eight to the horsepower," or about 93 watts.

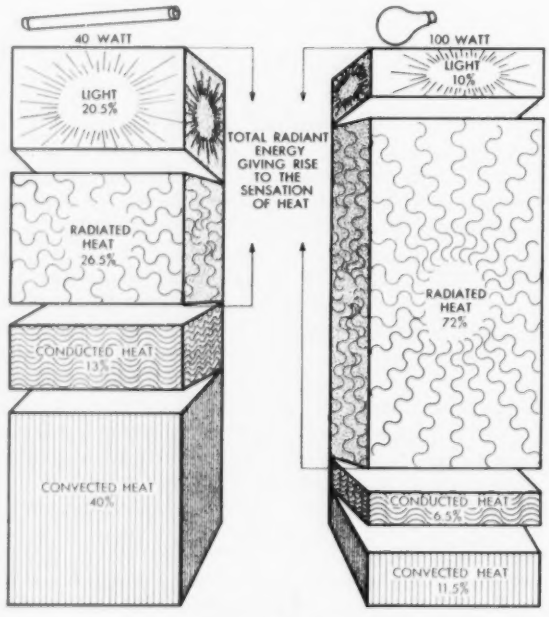


Fig. 2—Energy distribution of 40-watt fluorescent and 100-watt incandescent lamps. Each has about the same lumen output.

So the hunt for still more economical illuminants proceeds. No lessening of the zeal of lighting research is foreseeable.

In addition to the details of *what kind* of light is desirable, we may, in planning our lamps of tomorrow, question *how much* light is necessary or wanted? One excellent index of the growth in the use of light can be had from the growth of kilowatthours of electricity used for lighting, and of lamp bulbs (See Table III). The growth of population or the number of lighting users does not account for this entire increase. Rather, the larger number of jobs that light can do, plus the longer burning hours of comfortable or decorative light sources, suggest that power for lighting—and to a lesser degree the market for lighting accessories—about doubles every decade!

Significantly the growth-curve of lumen-hours in this country is rising much faster, or at a steeper slope, than that of the kilowatthours used for lighting. This means that (1) each watt is generating more light and that (2) as illuminants become more agreeable or more profitable to use, they are being burned longer.

But in the long look ahead, do we see the approach of a state of "lighting saturation," when man will see well enough, and need no more? "Not probable," says the scientist, because nature's light outdoors measures easily 9000 footcandles, while man's meager "standard" of 30 footcandles (as in schoolrooms or offices) is but *one third of one percent* of the values under which human seeing organs have developed. "Not likely," says the economist, because more and more light can be had from the same power—or the same dollars—and bargains generally increase usage. "Not safely," says the health authority, who recalls how darkness invites accidents. "Not wisely," urges the patrolman, for crime lurks in the shadows. "Not necessary," reiterates the research physicist, because man's methods of making light are constantly being improved, and expanded. "Not happily," urges the decorator or the homemaker, since light is always the magic wand that needs but touch the unnoticed or drab objects to bring them to prominent beauty!

Logical reasoning leads to the conclusions that we can well plan to use—and to make—more and better light, so how well do, or can, our illuminants perform today? What may tomorrow bring?

From the listing of Table II, and after the elimination of experimental lamps, we might choose for study the three most popular present illuminants, namely, the incandescent, the fluorescent, and the mercury lamps, in an effort to determine their capabilities of meeting tomorrow's needs, or their status in the foreseeable future. Part of this comparison is illustrated in Figs. 1 and 2, on the basis of today's efficiencies.

EFFICIENCIES OF SEVERAL ENERGY CONVERSIONS — TABLE I

Firefly, bioluminescence	Ratio of luminous energy / Radiant energy	= 90%
Electric power generation	Ratio of electrical energy / Coal energy	= 32%
Fluorescent lamp radiation	Ratio of internal ultraviolet / Input (socket) energy	= 60%
Fluorescent luminosity	Ratio of luminous energy / Elec. input energy	= 21%
Luminous (incandescent) radiation	Ratio of luminous energy / Elec. input energy	= 10%
Total (incandescent) efficiency	Ratio of luminous energy / Coal energy	= 2 to 3%
Photocell conversion (silicon solar battery, etc.)	Ratio of electricity / Sunshine light-fall	= 6 to 8%

INITIAL EFFICIENCY INCLUDING OPERATING ACCESSORY — TABLE II

Lamp	Lumens per Watt
100-watt incandescent lamp	16.3
1000-watt incandescent lamp	21.8
400-watt type E-H1 mercury lamp	45.0
1000-watt type C-H12 mercury lamp	48.0
180-watt sodium lamp (type NA-9)	45.0
40-watt (four-foot) fluorescent lamp	54.0
74-watt (eight-foot) Slimline fluorescent lamp	56.0
Experimental electroluminescent plate (optimistic)	12.0
Experimental tellurium-vapor lamp	20.0
Cold-cathode luminous tube (white)	40.0

GROWTH OF LIGHTING POWER AND LAMP BULBS (U.S.A.) — TABLE III

	Kwhr for Lighting	Lamps—Units
1920	12 billion	250 000 000
1930	20 billion	560 000 000
1940	40 billion	1 119 600 000
1950	100 billion	2 006 800 000
1960	150 billion (est.)	2 800 000 000 (est.)

The Incandescent Lamp

Based solely on the luminescent output (i.e., energy in the visible spectrum), the incandescent lamp under exceptionally good conditions generates about 30 lumens per watt (or 22 in a large 1000-watt general-service type). However, since its efficiency ceiling is established at the theoretical maximum of 53 (where the tungsten-alloy filament would melt), this light source has about reached its efficiency plateau. It will continue to be used mostly in those locations where the cost of electric power is especially low; where the burning hours are short; where the capital investment in equipment must be a minimum; or where mass decorative effects with a plurality of low-wattage (or low-voltage) bulbs are popular. It is essentially a home-lighting lamp, and also promises to remain superior for operation on batteries, or on direct current.

Among the probable final perfecting touches of the incandescent lamp will be decorative bulb shapes, and particularly the completion of a program to improve the white color and the diffusion, or the reduction of glare, of the everyday lamp bulb. This is done with an interior coating of silica. Some further reductions in bulb size will occur, but there is no prospect of any noteworthy improvement in filament material, inherent life, or color. As regards luminous efficiency, little hope of any consequential advances exists, even though in quite small bulbs of low wattage the use of krypton gas (instead of argon-nitrogen), with its very high atomic weight of 85, can conserve heat losses and add as much as 10 to 20 percent to the luminous output.

If the luminous efficiency of general lighting service lamps could be increased some ten percent, the theoretical value to the users in this country alone could be increased by one million dollars for each working day! However, pure output efficiency, without concomitant virtues of other qualities, may prove misleading or even valueless. Because the incandescent filament lamp does possess such virtues as sturdiness, divisibility into small wattages, convenience, and low unit cost, it will be with us for a long time. Still, the rewards of higher efficiencies entice us into the realms of metallic vapor—not metallic filament—light sources.

The Fluorescent Lamp

Leader of the vapor lamps, fluorescent illuminants offer more temptation to research and promise more immediately

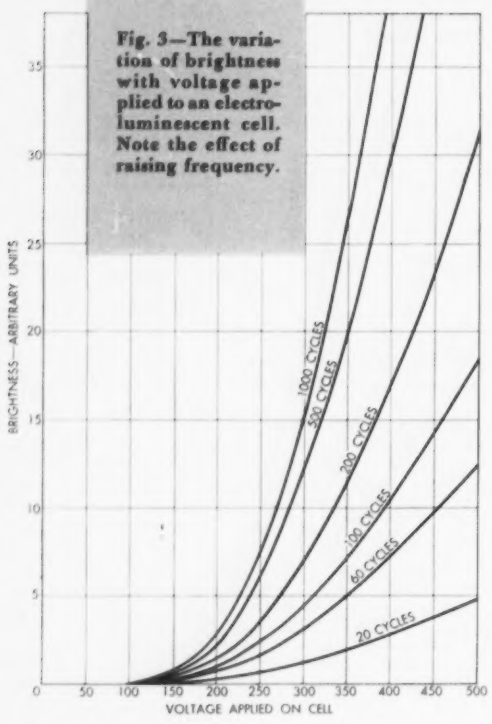


Fig. 3—The variation of brightness with voltage applied to an electroluminescent cell. Note the effect of raising frequency.

rewarding results. Today's good average efficiency of 54 lumens per watt can, under exceptionally good conditions and with today's production, be increased to about 70. A foreseeable optimistic figure of 100 to 125 is in the minds of many scientists. These gains are not the bursts of genius of a single individual. Patient workers in many fields toil long and hard for each percent of progress. And because the road is long, today's product is not prone to grow obsolete suddenly.

Certain fundamental losses seem likely to hold closely to present-day figures. There are known limits, such as the percentage of input energy that can be translated to ultraviolet (about 60 percent to 2537 A ultraviolet), and the percentage of ultraviolet convertible to visible light. Nevertheless, as is evident from Fig. 2, today's cool fluorescent lamp is not the heat radiator that the incandescent lamp always must be.

For existing installations, some 3 700 000 preheat fluorescent-lamp starters are consumed yearly, and are generally regarded as a mild nuisance. But in 1950 some 60 percent of all fluorescent lamps, up to the 40-watt size inclusive, used starters, whereas today's demand in new installations has reduced this figure to 40 percent, with corresponding increases in Slimline and instant-start types that need no starters. The rapid-start types are increasing, and are already up to 15 percent or better of the total recently installed. All this shows a trend toward simplicity, with hopes for better standardization and interchangeability.

On the near horizon is the clearing picture of such fluorescent illuminants as respond instantly to the switch; that have those color-tints so suitable in home decoration; and that are basically so economical that their destiny must soon expand in the extensive illumination of residences. Their variety of color-tints is almost unlimited. In effect, you just mix the phosphor "to taste."

Their versatility of size and shape is hardly less restricted, but in bulb forms—no! When not in more or less of the tubular shape, their great virtue of efficiency is lost. But if—and in this kaleidoscopic picture the "ifs" may be ponderable—we learn how to use the thermionic emission of electrons from an incandescent filament, these to generate added light when impinging on a special phosphor within the bulb, then the horizons enlarge once more.

The Mercury Lamp

The third common illuminant, the high-intensity mercury-vapor lamp, shows a slight spread between today's good maintained average and the performance of 50 lumens per watt (including ballast losses) recently achieved, which may yet be considered exceptionally good. This promising illuminant has rapidly grown to maturity, but seems not yet to have reached its full stature.

For this young and vigorous large-light source, the design improvements logically would be along lines of higher temperatures and pressures of the metallic vapor (which improve both efficiency and color), but these desiderata are limited by the refractory qualities of the inner tube or container for the arc. Since nothing foreseeable in a practical sense would improve upon today's use of clear quartz for these tubes, and since they are running as hot as is consistent with good life, the optimistic figure of 60 lumens per watt is about the best in sight.

Mercury lamps are generally used in places or sockets relatively difficult to reach, hence long life is considered a special virtue, even at the slight expense of utmost lumens. Today's lamps are rated 6000 hours. Most of tomorrow's may be nearer 10 000 hours—well over a year of continuous burning.

The mercury lamps of greatest immediate promise are the color-improved or fluorescent-mercury types (J-H1, C-H12, etc.) in sizes between 250 and 1500 watts, inclusive. In its simplest form, the clear mercury lamp emits light of a bluish-greenish-yellow color. It lacks red. But it has a fair surplus of ultraviolet, which once was wasted energy. So to transform this ultraviolet into visible red light, the outer bulb is coated with a magical fluorogermanate phosphor that fluoresces red, and the resultant pink flush mixes with the bluish-green light of the arc stream to roughly—and efficiently—simulate white light. When operated on prevalent 265- or 460-volt circuits, and using modern high-bay reflectors, the 1000-watt fluorescent-mercury lamp seems to be the least expensive source of industrial white light today.

Other color modifications are possible and promise to further expand the fields of application. One, recently developed for the illumination of large interiors, is a fused color coating or filter, which on the outside of the bulb reduces surplus yellow-green tints. Other betterments will follow. Street lighting and high-bay industrial areas will benefit most.

Light Sources for Tomorrow

The view ahead is exciting—challenging! Many of the illuminants are so radically different as to suggest revolutionary new lighting tools for a new and brighter era!

Among several illuminants under observation for reasons of special and rare characteristics, consider two that are diametrically unlike. Should either become commercially available, their use would be in unique, if not limited, fields.

1—*The tellurium-vapor lamp*, operating best on direct current, with metallic-pool electrodes (as did the Cooper-Hewitt mercury lamps of the gay but not too bright 90's), is noteworthy because of its continuous spectrum. Other clear-bulb vapor lamps usually have a line or broken spectrum when operating at the temperatures and pressures of practical illuminants. Directly the reverse of a black-body radiator, the

tellurium-lamp color at low temperatures is blue, but sunshine golden yellow at high (arc-tube) temperatures (some 700 degrees C). Theoretically its efficiency ceiling is about 82 lumens per watt, or in today's experimental lamps, at various loadings, between 15 and 40. Conceivably, it might serve well in a color-television studio.

The metal tellurium has such a warm-hearted affinity for other metals that the problem of building enduring electrodes in the quartz arc-tube remains a hurdle. This lamp's destiny lies altogether in the future. It is mentioned here chiefly to indicate how many are the peculiarities that beset the explorer of new light-lands!

2—*The electroluminescent plate*, or the device that enables the direct conversion of electrical energy to light through the excitation of a crystal phosphor, has, since its early studies of 1936, been viewed with more than casual curiosity. What a radical transformation of energy this "lamp" embodies! No hot filament, no bulb, no vacuum, no excited vapors—and no completely comprehensive explanations of just how this phenomenon of nearly "cold" light occurs.

A typical "lamp" consists of two thin electrically conducting surfaces, at least one transparent, separated by a dielectric film of phosphor. The phosphors most commonly tried have been zinc sulphides, or sulfo-selenides. Unfortunately, these are not too permanent, but the art is new. Areas of individual plates thus far achievable have been under a square yard.

The details of tomorrow's electroluminescent plates, or two-dimensional illuminants, are not fully worked out. Today it appears that these plates should operate best on high voltages (600 or higher) and on a-c frequencies upwards of 1000 or more cycles. As regards voltage, the brightness increases at a super-linear rate, while the increase with frequency is less than directly linear, but consequential. Also, over limited ranges and with certain phosphors, the increase in applied electrical frequency causes a shift towards shorter wavelength colors. Data reported by some observers (but subject to further study) shows some of the probable characteristics (Fig. 3).

Under optimum conditions, a brightness on the order of 100 foot-lamberts has been reported. The top efficiency may today reach as high as the 12 lumens per watt recorded in Table II (experiences differ), but the mass illumination of large areas seems not to be the role of this strange source. Rather, the luminous ornament or decoration, or the faces of clocks, instruments and meters, or signs. Alas, to grow up, this "lamp" may need many tomorrows! As in so many of tomorrow's lamps, the secrets lie in the magic of the crystal phosphors. How can they be kept permanent? How penetrated by the electrons, for excitation? How made exactingly impure? The prospective user must have patience.

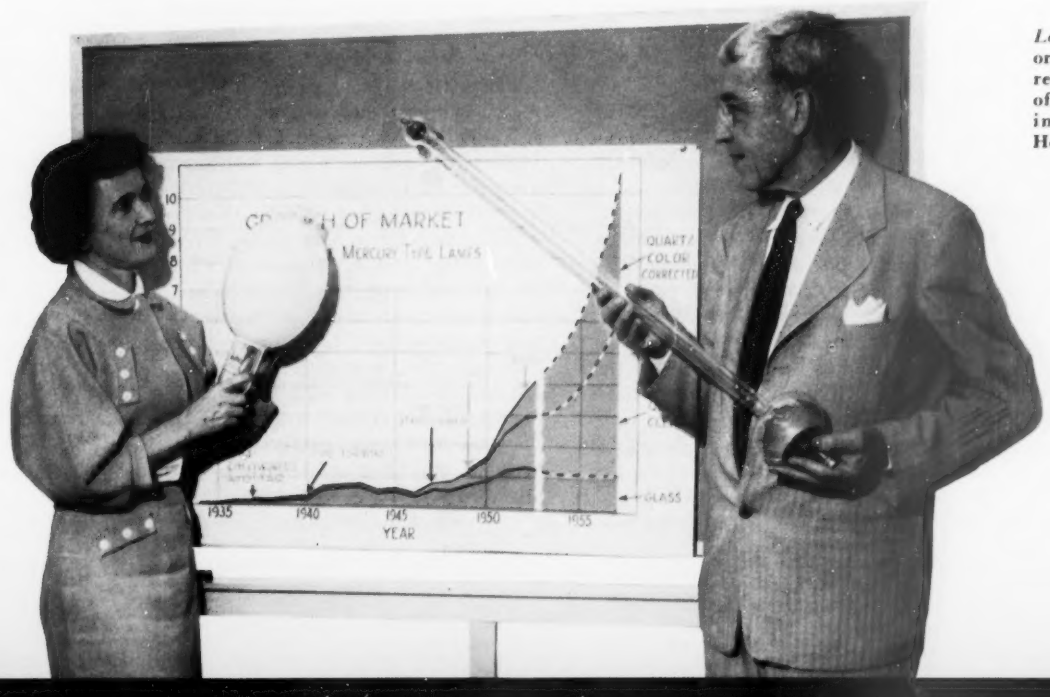
A Longer Look Ahead

Could we envision a simple transfer of direct current to high-frequency, high-voltage alternating current, then the solar battery on the roof—area for area—might provide power to excite a room ceiling of electroluminescent plates, to a brightness of some 50 foot-lamberts. This could mean, if the entire ceiling were used, a desk-top illumination of nearly 50 foot-candles. That is—while the sun were shining! And on the moon-rocket, or the interplanetary space island, what better method of obtaining power and light?

Could we but develop an enduring phosphor that would "soak up" light from the sun by day and keep it in a "deep-freeze" state, and later make use of it at night to emit light—that would open strange adventures in new lighting lands!

Then there are the beckonings of those embryonic light sources that need only a responsive phosphor to capture and convert to light the electrons streaming from selectively chosen hot alloys. This marriage of the incandescent and the fluorescent lamp might double the efficiency of the former. Practical bulbs of heavy quartz, filled with some 10 to 30 atmospheres of xenon gas, give us the intense white light of electric arcs, but as yet the cost is high. If we knew how to make a noncorrosive transparent container for hot caesium vapor, and could endure a water-cooled device, perhaps the future list of lamps would include a white-light source of a remarkable efficiency, approaching 180 lumens per watt. "Ifs" have a way of becoming "cans."

Even though we realize that today's power sources or fuels —coal, petroleum, wind, tides, nuclear fission—working through rotary machinery, are still to be the chief generators of man's light for decades to come, yet the various phenomena of producing light by always better methods—with or without new power sources—still challenge the inquiring mind.



***Left*, the modern color-improved or fluorescent-mercury lamp of 1954; *right*, original type Cooper-Hewitt lamp of 1901.**

Lightning Arresters

Station or Line Types?

Recent improvements in both station- and line-type lightning arresters necessitate a new look at each before a selection is made.

EDWARD BECK, *Manager, Lightning Arrester Sec., Distribution Apparatus Engineering, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania*

ADVANCES in the lightning-arrester art indicate that a revision of protective practices will permit economies. Both station-type (SV) and line-type (LVS) arresters have been improved. As a result, better answers can be given to the question that has plagued engineers for some time, "Where should the line be drawn between the application of station- and line-type arresters?"

The new line-type Autovalve arrester now is the approximate electrical equivalent of the previous station arrester, although not equal to the present station type. The line-type arrester has been improved in two major respects: (1) Maximum protective characteristics are slightly lower than those of the station arresters manufactured before 1954. (2) Their durability is almost equivalent to the requirements laid down in NEMA Standards for station-type arresters. At the time this was written, NEMA requirements were the most severe in any standards. They specify a discharge-current withstand ability for station arresters of 100 000 amperes with a wave shape of at least 5×10 microseconds; a duty cycle (combined surge and follow current) test of 20 operations with a discharge current of 10 000 amperes crest and a 12×45-microsecond wave shape; and an additional discharge-current withstand-ability test of 20 discharges of a square-wave shape having a current amplitude of not less than 150 amperes with a duration of 2000 microseconds.

The Autovalve line-type arrester (LVS) meets the 100 000-ampere and the 10 000-ampere duty-cycle test requirements, standard for the station-type arresters; it does not quite meet the square-wave requirement of 20 discharges of 150 amperes. However, this arrester does withstand 20 discharges of 100 amperes of 2000 microseconds' duration.

Service experience indicates that the most significant criterion of arrester durability is the duty-cycle test, because the principal function of an arrester is not only to discharge surge current but also to restore itself to an insulator after the passage of the surge current, by interrupting the follow current. The 10 000-ampere 12×45-microsecond test, with 60-cycle voltage applied to the arrester at the same time, has for many years been a routine test on Autovalve station-type (SV) elements. This has turned out to be an excellent criterion of expected field performance.[1] For more than a year the same routine tests have been applied also to Autovalve line-type arrester elements.

As mentioned, the protection afforded by LVS arresters is

as good as that given by station arresters built prior to this year. No lightning failure has been reported of a transformer protected by Autovalve station-type arresters installed adjacent to the transformer. Thus both the performance characteristics of the LVS arrester, plus experience with station-type arresters of the same or even slightly higher characteristics, indicate that the line-type arrester will give a high degree of protection to equipment adjacent to it. In the study of insulation coordination,[2] it does, in fact, take the place of the previous station arrester.

Where, then, should a line be drawn between application of station and line arresters? This is a question that has plagued engineers for some time. Manufacturers are frequently asked for their recommendations. This puts them in a difficult and sometimes embarrassing position, because the decision must be made by the user's engineers, based on many different considerations. The manufacturer can only present the facts on which the decision can be based.

There are differences, other than size of investment, between station- and line-type arresters. The discharge characteristics of Autovalve station-type arresters are lower than the line type by approximately 15 percent. Thus they provide a greater zone of protection.[3] That is, a switch, for example, can be located farther away from a station-type arrester installed on a transformer and get the same degree of protection that a line type would give it for a shorter separation.

In stations that operate at 69 kv and below, and are of small extent so that no large separations exist between pieces of equipment, the LVS arrester gives the most economical protection except under certain conditions mentioned later. Because it has somewhat lower durability than the station-type, occasional damage may occur to a line-type arrester, necessitating replacement. On the other hand, the cost of replacement is less, and probably an LVS arrester could be replaced at least once for the investment involved in a station type. Furthermore, service experience with LVS arresters—introduced in 1940—has been excellent.

In stations of 69 kv and below with different pieces of equipment widely separated, if multiple arresters located at strategic points are not practical, station-type arresters should be used. The lower characteristics of station-type arresters may in many cases provide margins larger than necessary, but many engineers feel that such margins are desirable. The fact that higher ratings of station-type arresters than line-type can be used and yet provide the same protective levels is sometimes an advantage. This may become quite important if system-voltage conditions make higher arrester ratings desirable. Where switching-surge duty is paramount, the station-type arrester should be used. However, the switching-surge hazard to arresters probably has been overemphasized, as few cases of damage in actual service are attributable to switching long lines or cables.

Where contamination is a serious problem, the station-type arrester gives better service and permits much longer periods between cleaning than the line type. As pointed out in American Lightning Arrester Standards, heavy contamination and excessive moisture are considered unusual service conditions and should receive special consideration. This admonition is not always heeded by users. Therefore it is of practical importance that station arresters are more suitable for contaminated conditions.

With severe contamination and moisture on the outside surfaces of the porcelains of high-voltage arresters, voltage distribution across the series gaps inside the arrester may be distorted. This distortion lowers the 60-cycle sparkover voltage of the arrester below the value obtained when dry or tested under standard AIEE wet-test conditions. If the internal 60-cycle sparkover voltage is depressed sufficiently, the arrester may be damaged. This effect is much more pronounced on line-type arresters because of their small diameter. Because of this small diameter, the contaminated surface of the porcelain is closer to the gap electrodes than in station types. Therefore, the influence of the outside surface conditions is more pronounced in the line-type arresters. Cases are known of repeated damage to line-type arresters in cement mills. Replacement by station-type arresters of the same rating eliminated further difficulties.

The influence that wet contamination on the outside of the arrester exerts on the internal sparkover is the reason why line-type arresters and ratings above 73 kv are not generally recommended. Tests made on arresters of both types rated 90 kv indicate that with the surface badly contaminated and wet, the 60-cycle sparkover of the station arrester drops 8 percent while that of the line type drops almost 40 percent. A line-type arrester with a dry 60-cycle sparkover just on the AIEE requirement of not less than 1.5 times rating, would drop to 0.9 its voltage rating under such contaminated conditions. This makes the arrester vulnerable to damage. In stations operating at voltages higher than 69 kv, the station-type arrester is definitely recommended.

To summarize the situation, reappraisement of lightning-arrester performance indicates that in stations operating at voltages higher than 69 kv, station-type arresters should be used. In stations operating at voltages of 69 kv and below, the LVS arrester will give highly satisfactory protection, comparable to that obtained with station-type arresters manufactured prior to 1954. If these stations contain widely separated equipment, or if they are subjected to considerable contamination, then station-type arresters are advisable. Adoption of practices as outlined above would permit considerable economies on systems operating at 69 kv and less.

REFERENCES

1—"Control of Lightning Arrester Quality," by T. L. Dyer and Edward Beck, *Westinghouse* ENGINEER, May, 1951, p. 100–1.

2—"Insulation Co-ordination," by C. F. Wagner, R. L. Witzke, E. Beck, and W. L. Teague, *AIEE Transactions*, Vol. 71, 1952, p. 1064–80.

3—"Surge Protection of Transformers Based on New Lightning Arrester Characteristics," by J. K. Dillard and T. J. Bliss, AIEE Transactions Paper 54–302 (not yet published).

BOUND VOLUMES . . . INDEXES
. . . The *Westinghouse* ENGINEER

Index for the 1953–1954 issues of the Westinghouse ENGINEER will be available about January 1 on request, without charge. Copies of the 1951–1952 index are also still available on request.

Cumulative Indexes for the years 1941–1950, containing all the material published in the Westinghouse ENGINEER to the end of 1950 are available on request, without charge.

Permanent Binding of your 1953–1954 issues can also be provided about January 1. Send your 12 issues (6 per year) to the address below for binding into a durable, attractive book with index. The cost: $3.75. Missing copies will be supplied at 35 cents each, additional. A complete bound volume, which contains the issues for 1953–1954, will also be available at $6.00, postpaid.

The *Westinghouse* ENGINEER
P. O. Box 2278, Pittsburgh 30, Pa.

MATERIALS DE
for the Submarine Th

WILLIAM A. JOHNSON, *Manager, Materials Dept., Atomic Power Div.*

Developing a nuclear reactor involves a whole host of difficult problems. One of the most trying is that of materials.

FROM THE earliest days of the Manhattan District, materials problems have severely limited the design and operation of atomic piles. The problems arise from requirements unique to nuclear reactors. Some materials are required to moderate, that is, to slow down, neutrons; graphite, beryllium, and water are examples of such materials. Other substances are used in the internal structure of the reactor and must be transparent to neutrons; aluminum, magnesium and zirconium are examples. Still different materials are used to shield personnel from the dangerous radiation generated in an atomic pile; lead and concrete are best known for this particular type of application.

Because of the large number of high-energy particles formed during nuclear processes, atoms of a metal are knocked out of their normal lattice positions or transmuted to atoms of a different element. Frequently, the result is drastic changes in the properties and dimensions of the materials. Thus, structural applications involving high levels of radioactivity require metals resistant to irradiation effects. Corrosion frequently dissolves significant quantities of materials ordinarily considered corrosion resistant and the coolant may thus become highly radioactive, making access to the piping and heat exchangers difficult. The latter problem has been solved in a few cases by slightly modifying the composition of well-known materials, such as type 347 stainless steel used in piping, valves, heat exchangers, etc.

Materials problems connected with early reactors were increased in complexity and new problems were added by the design conditions of the submarine power plant. High neutron flux density intensified the radiation-damage effects. The higher operating temperatures needed to obtain significant quantities of useful energy produced serious corrosion problems. Further, the operating requirements of a war vessel—such as shock—required good strength at elevated temperatures.

The greater part of the materials development program for the submarine thermal reactor was concerned with three problems: the development of materials to satisfy the nuclear requirements; the selection of structural materials that would operate satisfactorily in the high-temperature, high-pressure water; and the development of methods for maintaining the purity of the water coolant.

Zirconium

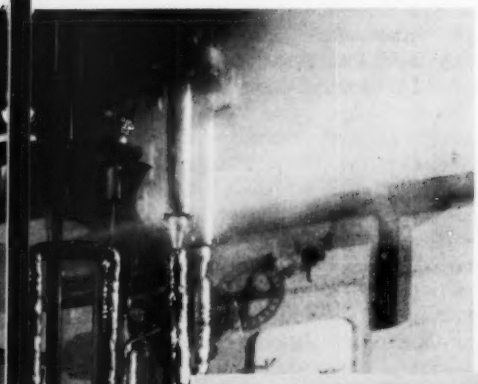
The most serious problem was the selection of a metal for structural applications within the reactor itself. Such a metal must be transparent to neutrons, be easily fabricated, have good corrosion resistance to high-temperature water, and meet the strength requirements. Furthermore, the material must be, or have good prospects of becoming, readily available. Only zirconium satisfied these requirements.

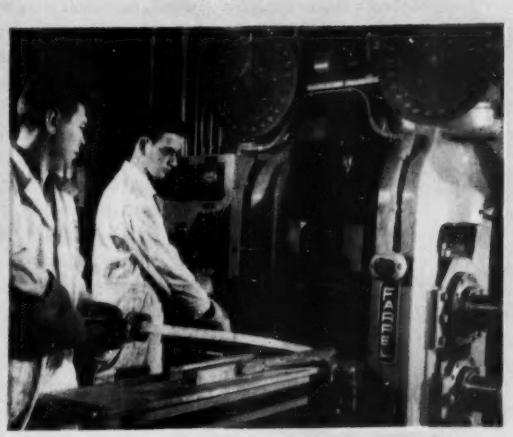
In early 1949, when zirconium was chosen as the reactor structural material, practically nothing was known of its technology and properties. The Bureau of Mines plant at Albany, Oregon had a small facility for producing sponge zirconium by the Kroll process and some equipment for melting this sponge to small ingots suitable for forging and rolling into

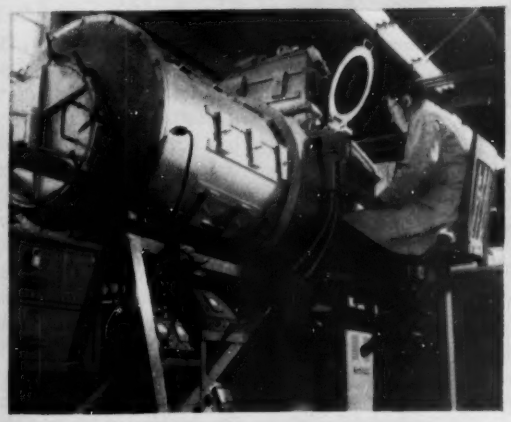
VELOPMENT

hermal Reactor

iv., Westinghouse Elec. Corp., Pittsburgh, Pa.







Left, newly made zirconium crystal bars get a steam cleaning. *Below,* ingots of zirconium are rolled into slabs in this mill. *Bottom,* in this giant vacuum tank many zirconium parts for the reactor were welded.

useful shapes. The Foote Mineral Company in Philadelphia was the only commercial producer of crystal-bar zirconium, the highly refined form of metallic zirconium. It was quickly determined that zirconium melted from the Kroll sponge then available had unsatisfactory corrosion resistance. The supply of crystal-bar zirconium was far short of the amount required for the Mark I plant (prototype of the submarine reactor). After a short development program using a small pilot model, the Westinghouse Atomic Power Division established a facility for producing this type of zirconium in the required amounts.* Within 14 weeks, production facilities were designed, constructed, and put into operation. At the peak of the program the plant produced thousands of pounds of zirconium per month. This crystal bar was purer than any previously produced, the total impurity content amounting to only 0.05 percent.

Effect of Impurities on Corrosion Resistance

The sensitivity of the corrosion resistance of zirconium to impurities can be illustrated by comparing the impurity content of sponge zirconium and crystal-bar zirconium to that of better-known metals. Sponge zirconium is equivalent or better in total impurity to commercially pure metals such as 2S aluminum and Armco iron. Crystal-bar zirconium is equivalent in total impurities to many "chemically pure" metals. As previously mentioned, the sponge zirconium available in 1949 was totally unsatisfactory. Crystal-bar zirconium, while satisfactory, required careful handling in order to maintain the desired corrosion resistance.

Corrosion tests were performed in autoclaves filled with a mixture of water and saturated steam at high temperature. The large variation in corrosion resistance shown by these tests, which sometimes occurred within a single crystal bar, indicated that a study of the effect of segregated impurities was needed. It was determined that four elements—carbon, nitrogen, aluminum, and titanium were most damaging to the corrosion resistance.

Nitrogen was found to be the most important impurity, since hot zirconium absorbs it very readily. In fact, the only previous commercial application of zirconium was as a "getter" for air in vacuum tubes. Thus, all fabrication steps that involved heating zirconium above 300–400 degrees C required extraordinary care to exclude any contamination from the atmosphere.

Even when harmful impurities were excluded, variations in the corrosion resistance were often observed. One cause of variability was residual stresses remaining in the metal surface after machining. Since high-temperature annealing was likely to introduce contamination, the stressed surface layers were removed by etching. The only satisfactory etchant for zirconium available at that time contained fluoride. If fluoride residues were not removed by careful rinsing, the corrosion resistance was lowered. The cleaning procedures developed were almost surgical in nature.

*The production of crystal-bar zirconium is discussed in the September, 1953 issue of the *Westinghouse* ENGINEER.

Still other variations in corrosion resistance occurred. Occasionally, when the water level in an autoclave dropped, exposing zirconium to steam, the exposed metal corroded while the metal under water was satisfactory. This was traced to the presence of nitrogen, which concentrated in the steam. Very careful de-aerating procedures were necessary, both during the corrosion test and during reactor operation.

Physical and Mechanical Properties

A very close control of those physical and mechanical properties of zirconium that affected fabricability and stability was found to be necessary. Much variation in mechanical properties was found in lots of zirconium that presumably had the same chemical composition and prior treatment. Studies revealed that zirconium does not recrystallize in the manner of most other metals, and equiaxed or regular grain structure does not indicate that the material has been fully annealed. Fortunately, careful hardness measurements were found to be trustworthy for controlling the extreme annealing sensitivity of zirconium.

Although zirconium has a hexagonal crystal structure, which ordinarily corresponds to low ductility, crystal-bar material can be reduced 99 percent by cold rolling with only a small amount of edge cracking. Slight traces of oxygen, however, decreased ductility drastically. The ductility was also affected by heat treatment. Zirconium quenched from 600 degrees F was quite ductile, but zirconium air cooled from 600 degrees F was brittle. It was found that the embrittlement resulted from the presence of a very small amount of hydrogen, apparently absorbed during the corrosion test. This result was surprising since previously available data indicated that zirconium would dissolve large amounts of hydrogen. Since the small amounts of hydrogen found to embrittle are quite difficult to remove, very careful control of processing was required.

Melting of Zirconium

The diameter of the crystal bar is about $\frac{5}{8}$ inch, which is too small to fabricate directly into reactor components. The high chemical reactivity of molten zirconium causes it to reduce or dissolve all crucible materials. The best crucible material is graphite but, as previously mentioned, carbon contamination seriously diminishes corrosion resistance. Consolidation of crystal bar by hot pressing produced a high-quality product but was slow and costly, and was not capable of conveniently producing sufficiently large pieces.

Modifications of laboratory furnaces that used tungsten electrodes and water-cooled copper crucibles were made, and the resulting furnaces were capable of producing a 4-inch diameter, 35-pound ingot. A furnace was later designed that produced a 6-inch diameter, 100-pound ingot. These furnaces were very similar to those commonly used in the melting of titanium.

The basic characteristics of the arc furnace (Fig. 1) were: (1) a water-cooled copper crucible in which the metal was melted without contamination from the crucible; (2) provisions for an inert argon or helium atmosphere of high purity, which allowed melting with a minimum pickup of impurities and made it possible to maintain a stable arc; (3) a water-cooled electrode holder that kept the tungsten-electrode tip at a temperature low enough to minimize contamination of the melt by tungsten.

To insure good melting conditions in the furnace, crystal bar was rolled down to rod and sheared into pellets. The pellets were cleaned and charged into the furnace hopper, which was then evacuated and filled with a mixture of helium and argon gas.

The arc was struck at 400 amperes between a piece of zirconium placed in the bottom of the crucible and the tungsten electrode. Zirconium pellets were introduced into the furnace by a vibrator feeder and when molten metal covered the bottom of the crucible, the power was gradually increased until a current of 1200 amperes at 50 arc volts was obtained.

Actually, the arc-melting process can be thought of as progressive welding, with a molten pool of metal one quarter to one half inch deep. The depth of this pool remains approximately constant. As fresh metal is charged and melted the bottom portion of the pool freezes. Thus at any time during melting, the major portion of the ingot is solid. During melting, as the ingot is built up, the electrode is automatically withdrawn, since the arc-voltage control keeps the arc voltage (arc length) at a predetermined value. A 35-pound ingot is produced in about $2\frac{1}{2}$ hours.

By proper control of melting conditions, such as rate of feed and crucible cooling, sound ingots were produced. As in other steps of zirconium processing, great care had to be taken to exclude atmospheric contamination.

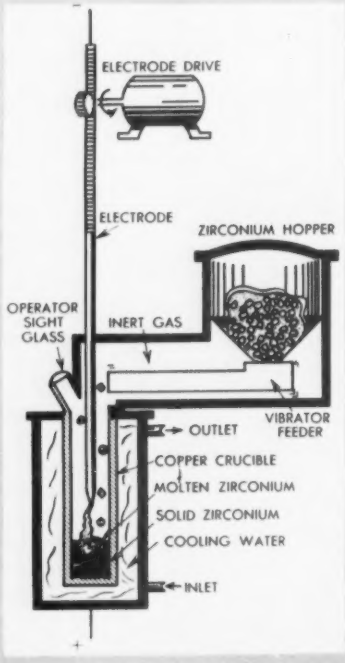


Fig. 1
A schematic diagram of the arc furnace used for producing zirconium ingots. Current is 1200 amps at 50 arc volts.

Other Problems in Zirconium Fabrication

In hot-forming operations where surface contamination was objectionable, the zirconium was protected by a metallic jacket. Techniques were developed for jacketing various shapes with copper and steel. In the case of steel it was found necessary to use Tinamel, a steel in which dissolved gases are "fixed" by titanium additions. The jacketed part was evacuated, welded shut, and tested to insure no leaks prior to hot forming.

Design considerations required that much of the joining of the zirconium reactor components be by welding. Inert gas welding was used. All welding was accomplished in an airtight box, which was evacuated to less than 0.03 micron of mercury pressure to remove practically all of the air, and then filled with about one-atmosphere pressure of helium. The welding motions were controlled remotely. The mechanism was de-

signed to operate with no lubrication. Special seals for introducing motion to the positioning apparatus were developed, which were both vacuum and pressure tight. The components produced in these welding boxes were mechanically strong, dimensionally true, and possessed adequate corrosion resistance properties.

The residual stresses introduced in welding had to be removed in order to prevent warping of the part during reactor operation. Two vacuum furnaces, 15 feet high by 3 feet in diameter, were designed and constructed. These were, and perhaps still are, the largest such furnaces ever built, and incorporate an elevator to move the parts between the cooling and heating chambers. Westinghouse 4000-cfm pumps, which had been constructed for the Manhattan District, were used to produce a vacuum of less than 0.03 micron.

Materials for Non-Nuclear Applications

Available data on the use of familiar materials in supersaturated steam at temperatures up to 1100–1200 degrees F were not very applicable to conditions in the submarine thermal reactors. It was soon discovered that the corrosion and wear resistance of materials in this environment was not necessarily indicative of their resistance in hot water. Thus, an extensive testing program was required to evaluate these ordinary materials.

The solubility of materials such as stainless steels in very high-temperature water contaminates the water and weakens the material. Contamination of the water fouls heat-transfer surfaces of both the reactor and steam generators. The impurities in the water become radioactive. Because of the high stresses generated in certain parts, the weakening effect was serious. Many bearings were necessary in the various mechanisms required, i.e., control drives, valves, pumps; thus, wear resistance of various metal combinations, under conditions where the only lubrication was low-viscosity water, required extensive study.

The serious corrosion problem was thought to require the use of a stainless steel stabilized against the precipitation of chromium carbide and resultant intergranular corrosion. Commercial AISI type 347 stainless steel achieved this stabilization by the addition of niobium, which combines chemically with the available carbon, leaving none to react with the chromium. However, all niobium used in commercial steels contained varying amounts of tantalum, which becomes highly radioactive when exposed to neutrons. It was found necessary, where type 347 stainless steel was used in that part of the system exposed to high neutron flux, to specify a lower tantalum content and correspondingly higher niobium content than usual in standard commercial steels. It has since been found that unstabilized austenitic stainless steel is satisfactory for the majority of reactor applications.

The complicated structure contained many crevices. Such crevices are often found to corrode more rapidly than exposed surfaces, presumably because of the formation of an oxygen cell brought about by depletion of oxygen within the crevices. Where crevices could not be eliminated by changes of design, the difficulties were minimized by careful selection of material combinations and proper adjustment of water composition.

Because the high pressures employed required the use of thick sections, welding of the stainless steel was a very serious problem. This steel was subject to cracking during welding and during the subsequent heat treatment. Insofar as possible, Mark I components were fabricated in accordance with applicable ASME standards, which specify a stress-relief anneal for weldments made from austenitic stainless steel. On many parts it was necessary to waive this requirement to avoid cracking in heavy weldments. Subsequently, approval was given by the ASME to modify the annealing requirements. The joining of dissimilar metals presented many additional problems. It was necessary to weld such metals as stainless steel to carbon steel, Inconel to stainless steel, hardenable martensitic stainless steel to non-hardenable austenitic stainless steel, and cupronickel to stainless steel. Because of the danger of air-borne contamination, completely leak-tight joints were required. For example, the welds between Inconel cans and stainless-steel jackets of pump motors must withstand a high differential water pressure with zero leakage. Also, for example, a failure of the joint between heavy cupronickel pipe used for the sea-water heat exchanger and the stainless-steel system would produce a loss of coolant from the primary system, with serious consequences. This joint must withstand high thermal shock stresses as well as, of course, mechanical shock and hydrostatic stresses.

This is a "canned" motor-pump; units of this type were developed for the *Nautilus*. Both rotor and stator of the motor are canned in Inconel, and radioactive water being pumped passes between them.

Wear of Materials

As previously mentioned, wear problems were unusually serious because of the complete lack of data on the subject in the reactor environment. The austenitic stainless steels, which were the basic structural materials, were quickly found to be unsuitable. Galling occurred with a relatively small number of rubbing cycles. Materials recommended by bearing manufacturers usually had poor corrosion resistance while materials satisfactory in corrosion were usually unsuitable in regard to wear. After thousands of tests, a few satisfactory combinations were obtained. An outstanding one was a hardened stainless material coated with industrial hard chrome plating, which was operated in contact with Stellite. This combination has the fundamental disadvantage, however, that improperly prepared hard chrome plate can produce

flakes, which in turn can produce excessive erosion or sticking. Since no nondestructive, highly certain test could be devised for testing the quality of chrome plate, an elaborate test was used to rate commercial platers, and only plating from approved sources was employed.

Other Problems

The combination of corrosion, weldability, wear, and general metallurgical quality, plus the serious consequences of a component failure during operation, required quality standards far in excess of any normally used. In many cases, full-scale mock-ups were required to develop the most desirable fabrication techniques. Entire assemblies were corrosion and shock tested. Extensive inspection operations were performed on essentially all of the many components used in the Mark I nuclear power plant.

Primary Coolant Development

Properties of the primary water coolant seriously affected the operation of nearly all reactor components. Corrosion products circulating through the system can cause failure of mechanisms by hindering the motion of moving parts. Impurities become radioactive and consequently lengthen the time after shutdown before access of personnel to the reactor compartment is possible for maintenance. Deposition of impurities on boiler tubes and heat-transfer surfaces in the reactor can seriously affect heat transfer and operating temperatures in the plant. Thus, a large program was conducted aimed at reducing the corrosion and removing corrosion products from the system.

Water that goes into the nuclear reactor must be chemically pure to reduce corrosion and radioactivity.

Impurity requirements of the primary coolant water are much more rigid than those encountered in normal power plants. The usual boiler plant is concerned with compounds of calcium, magnesium, and silicon, which foul boiler tubes, and chlorides and the like, which produce corrosion. The problem is usually taken care of by: (1) preparation of the water to reduce the quantity of materials introduced into the system, and (2) treatment of the system water to prevent formation of undesirable deposits. In the submarine thermal reactor, however, the induced-radioactivity problem required that almost all foreign materials, including deposit inhibitors, be absent from the water. For example, water containing one part per million of sodium, which might be introduced by leaks from the sea water evaporators, would become highly radioactive. It was necessary to develop and install a purification system composed of filters and ion exchangers, and operating on a bypass stream at high pressure, to continuously purify the water in the primary system. A filter was developed that can remove particles of insolubles whose size is less than one micron. Extensive modification of ion exchangers was necessary since their use at high pressure was rare or even perhaps unique. A program was required to insure that the ion-exchange resins were stable to both temperature and radiation. The result was a purification system that maintains reactor-water purity at a few tenths of a part per million total impurity.

Water Dissociation

Theoretical studies indicated that there was a large likelihood that water would be dissociated by radiation into its component elements—hydrogen and oxygen—and that these elements might be in an extremely active form that would react undesirably with components.

Elaborate experiments were set up in existing reactor facilities to measure this radiation-induced phenomenon in both static and dynamic systems. It was found that the rate of dissociation of water and the rate of recombination of the hydrogen and oxygen, under normal reactor operating conditions, were such that the steady-state concentrations of the two gases were negligible. The recombination rate, however, is quite sensitive to impurities that may be present in the water. Since it is practically impossible to remove all impurities from the water system, considerable study is still under way on the problem.

Corrosion in Reactor Systems

Three different systems are required for a complete study of corrosion. Tests with autoclaves are suitable for screening a large number of samples, but it is difficult to control the water composition in such tests. Dynamic tests out-of-pile can measure corrosion-erosion and water-composition effects. The difference between the results of the tests is best illustrated by the fact that certain materials show a weight gain in an autoclave test and a weight loss in a dynamic test. Neither theory nor data, however, gave much assistance in estimating the effect of radiation on corrosion. To obtain precise information, a complete dynamic system simulating quite closely the conditions in the submarine thermal reactor was designed, constructed, and installed in the highest neutron-flux reactor available. Thus, a radiation-corrosion test of a production fuel assembly, as well as a system test where corrosion, water purity, water activity, and water dissociation were measured, was performed prior to the start of the Mark I reactor. This simulated submarine thermal-reactor test proved tremendously valuable. Several very serious and unanticipated problems were uncovered. Fortunately, adequate solutions were found.

Developments Subsequent to Mark I

The crystal-bar process produced zirconium that was costly and required extraordinary care during fabrication and use to insure its adequacy. The logical next step was the development of alloys that could use the cheaper sponge directly, have improved properties, and that did not require the involved and costly fabrication process used for crystal-bar zirconium. This development has been made and the Mark II submarine thermal reactor will use such an alloy. Work is continuing on still better alloys. At a slower pace, developments are being made in ion-exchanger resins, filter materials, and alloys suitable for use in bearings. A serious hindrance to all development is the lack of adequate facilities for in-pile testing. Despite these difficulties, however, materials knowledge is being accumulated rapidly.

Transformer Insulation Power Factor

What Does It Mean?

The relative importance of transformer insulation power factor has been the subject of considerable discussion. Actually its value must be weighed against many factors.

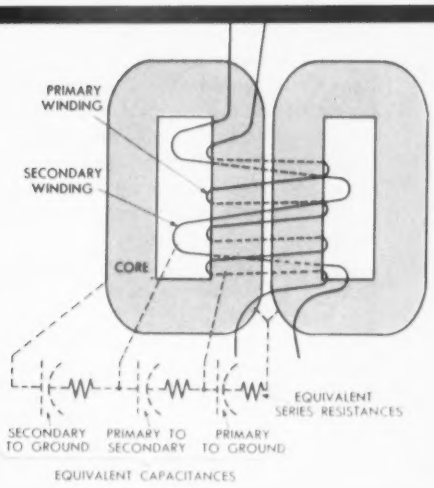


Fig. 1
Dielectric loss of each capacitor divided by capacitive volt-amperes is equal to power factor.

E. C. WENTZ, *Manager, Power Transformer Development, Transformer Div., Westinghouse Electric Corporation, Sharon, Pa.*

MEASUREMENT of power factor of transformer and bushing insulations has received considerable attention during the past 20 years, but much of this has not been particularly scientific or objective. And because an extensive program of measurement in the field requires expensive equipment and a skilled organization, there has been a tendency, at times, to claim more than the obvious value of such a program.

In some instances, the emphasis on insulation power factor has resulted in demands for low power factor of insulation in new transformers. Designers of these transformers have been unable to confirm this need, yet have generally refrained from contradiction lest they appear to advocate high power factor. Yet it seems that designers should be able to contribute pertinent data, and a sensible analysis of this data because of their intimate knowledge of transformer insulation.

Initially a negative attitude is unavoidable, for it is necessary, from a scientific viewpoint, to consider all aspects of power factor in logical order; this results in finding out that many things *cannot* be learned. However, the final conclusions of a positive nature should be of some permanent value.

What is this insulation power factor? Any winding of a transformer is separated from the other windings and ground by insulation, which forms an effective capacitance network as indicated in Fig. 1. In each capacitance are dielectric losses, which can be conveniently represented by a resistor in series with the capacitor. The insulation power factor is commonly defined as the ratio of the resistance to the impedance of this combination.

How is this power factor measured? The same way it is measured in any capacitor; apply a voltage and measure amperes and watts, or use any number of a-c bridge circuits to determine the effective resistance and capacitance, then calculate power factor.

Having measured the power factor, what use can be made of the result? One line of reasoning says that if a given voltage is applied to the equivalent capacitor, a calculable dielectric loss will be developed in the insulation (in the equivalent resistor in Fig. 1) and this loss will cause some heating in the insulation. Perhaps the insulation will get too hot, and perhaps not. The heating effect can be calculated fairly well only if all dimensions and thermal characteristics of the materials are known.

What else can be learned from this power-factor measurement? From the measurement alone, not a thing. A single power-factor measurement tells nothing but the possible dielectric loss, and often not even that much. Yet at this point transformer designers usually hesitate to discuss it further. Designers are reluctant to point out that dielectric losses are usually entirely harmless lest they appear to say that these losses are a good thing. Of course the dielectric loss is a good thing to know; the designer can tell whether it is high enough to cause destructive heating, and guard against it. But it is very difficult for anyone but the designer to make much that's factual out of it.

However, an inquisitive investigator many years ago discovered that if he heated paper insulation, power factor increased rapidly with temperature, but that after it had cooled again, the power factor usually was lower than before. From this it was deduced that power factor increases with temperature, but also decreases if the paper is dried out.

If the paper is humidified, or the moisture content increased, power factor increases. Because moisture is almost always present as a possible contaminant, it is natural to suppose that if power factor increases, moisture is the cause. However, this is only a strong supposition; many other things can happen to increase power factor.

The physicists and chemists help at this point. They have studied the molecular behavior of dielectrics and know something about what goes on within a dielectric to cause the loss, and from this can deduce more general ideas about moisture and power factor.

They say that moisture causes mineral impurities to ionize,

or break down into two oppositely charged particles that can move more or less freely through the insulation when voltage is applied, losing energy by collision with other molecules and causing dielectric loss.

There are also dipoles, or polarized molecules, that can rotate in a viscous manner in response to the electric field, causing dielectric loss. However, this leads to the conclusion that the dielectric loss does not depend on moisture alone, and that some contaminants may cause high power factor even though moisture is not present in the insulation.

And so they do. The power factor of transformer oil, for example, is sensitive to almost any material that can be dissolved in the oil. Some resins and asphalts in small quantities increase the dielectric strength of oil as measured by the standard test method, but also increase the power factor to many times the original value. The quantitative relations between amounts of most of these contaminants and the dielectric properties of oil, and the variation of resulting dielectric properties with temperature, are a subject that is nearly a closed book.

This indicates that not enough is known about insulation to be able to deduce anything from a single power-factor measurement. This is especially true when the insulation is a complicated structure containing several different materials, as it usually is in a transformer.

In a completed transformer (Fig. 1) the equivalent capacitor is formed by one winding as one electrode and the other winding, core, and case connected together as the other electrode. The dielectric structure is composed principally of paper, oil, and possibly one or more kinds of resinous binders. It is so complicated that if power factor is high, the cause is unknown and only a suspicion exists that dielectric loss may cause trouble.

If the designer suspects that the dielectric loss is high enough to affect the serviceability of the transformer, and removes and tests each piece of material separately, he can soon determine where the dielectric losses are and whether or not they will cause excessive heating. If the rise in temperature causes a further increase in dielectric loss that is more than can be dissipated at the higher temperature, the rise in temperature and loss may continue without limit until a hole is burned in the insulation.

If the designer studies power factor on this basis, he will generally find that transformer insulation is not stressed sufficiently to develop high dielectric losses, even in high-power-factor material. Also, that the ventilation required to carry away the copper loss easily takes care of the relatively negligible dielectric loss; usually the power factor can be 20 percent or more in properly ventilated oil-filled transformers without causing undue dielectric heating. In certain plastic-filled instrument transformers in which the insulation is not well ventilated, cumulative heating has been induced in insulation having a power factor of 20 percent. The insulation in high-voltage bushings, which is stressed rather highly and is not particularly well ventilated, can develop cumulative heating at 20-percent power factor. These are only typical values as measured at room temperature, but they confirm the idea that power factors much higher than are common in actual transformer insulation can be logically defended and justified.

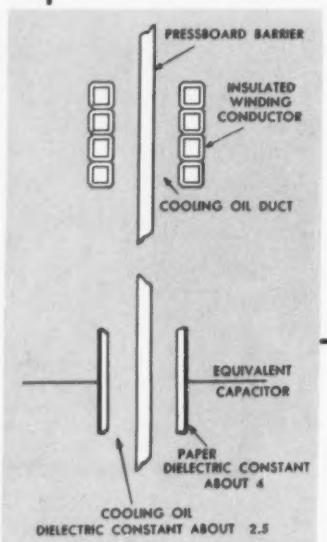
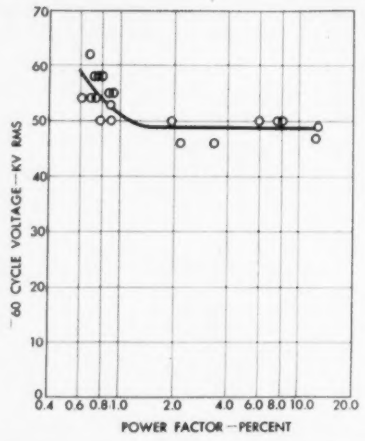


Fig. 2
Dielectric stress is inversely proportional to the dielectric constant of the insulation.

Fig. 3
Sixty-cycle, one-minute step-by-step puncture strength of oil-impregnated pressboard.



Another reason for low dielectric loss in transformers is that solid insulation practically always must be used in series with oil used for cooling. The oil must be admitted very near to the conductor surface if hot spots are to be avoided. Oil cannot be stressed nearly as high as paper or pressboard because corona discharges result, and yet, because of the *low dielectric constant* of oil, the *unit dielectric stress* in the oil actually becomes *higher* than in the pressboard with which it is used in series. Therefore, to keep the stress below the corona level in the oil, the stresses in the paper and pressboard are relatively low and the resulting dielectric loss is very small, even if the power factor is high (Fig. 2). This highly stressed oil generally has a very low power factor and, being liquid, is not subject to cumulative dielectric-heating failure anyway. This is another reason why the permissible power factor can be so high without risking failure.

Suppose the designer "purifies" his insulation so that no materials with relatively high power factor are used, and that he is careful to eliminate any materials that can dissolve in the oil in minute amounts, and thus raise the power factor. Suppose that at some extra expense he makes a low-power-factor transformer? Can he claim advantages for it? Would it then be possible to use power-factor measurements to demonstrate proper drying of insulation? Does dielectric strength of insulation become appreciably higher if it is made very dry? An interesting and unfortunate commentary on the history of power-factor measuring is that until recently there was no published information relating moisture content, power factor, temperature, and dielectric strength in oil-impregnated pressboard, the basic insulation of most transformers (see Table I).[9]

The fact that the dielectric stress in the solid insulation is lower than that in the oil means it is not the limiting factor in determining the overall strength of the transformer insulation structure. Insulation with five-percent power factor (Table I) has nearly as much strength as insulation with two-percent power factor. However, the difference in strength of the com-

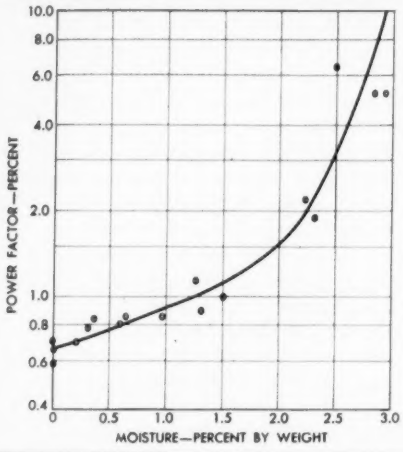


Fig. 4
Variation of power factor with the moisture content of oil-impregnated pressboard.[9]

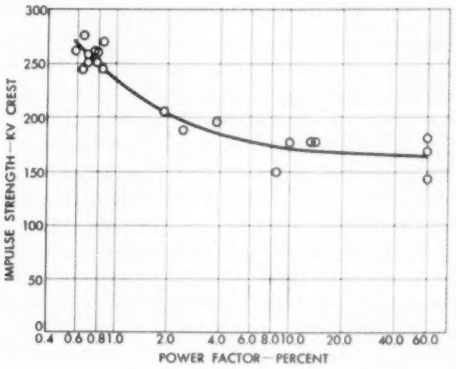


Fig. 5
Impulse puncture strength of oil-impregnated pressboard at different power factors.[9]

plete transformer structure as built with two- or five-percent power-factor insulations would be much less than the difference in dielectric strengths of the two materials themselves; and it would probably be most difficult to find any real difference. From this point of view, insulation of five-percent power factor is as adequately dried as that of two-percent power factor.

Another effect of moisture is that it accelerates deterioration of insulation as measured by loss of tensile strength.[6] It is doubtful that deterioration of insulation in service would be as rapid as deterioration measured in the test tubes. Clearly, however, the presence of moisture does actual harm to insulation, which, moreover, is permanent damage; that is, the additional loss in mechanical strength of insulation caused by the presence of moisture during a long period of service is not regained when the transformer is dried out. Drying reduces the rate of deterioration (loss of mechanical strength), but the previous loss is never recovered.

Considerable doubt exists as to whether the loss of mechanical (tensile) strength really represents deterioration. Certainly the loss of dielectric strength is much less than the loss of mechanical strength. However, the insulation is structural, and is the first member to absorb stresses from the coils. The vibratory forces of a short circuit tend to shred the insulation, and the resistance to this is probably related to tensile strength. If this is true, moisture is a bad thing in itself because it accelerates deterioration. The conclusion is that moisture addition that raises the power factor from 1.5 to 3.0 percent (change from 2.0 to 2.45 percent moisture) will reduce by 20 percent the time it takes to lose 75-percent tensile strength (from 126 to 103 hours at 120 degress C under test-tube conditions).

Such a reduction may not be realized in service, but good judgment argues the wisdom of trying to get down to a moisture content corresponding to 1.5-percent power factor in pressboard insulation, providing it can be done at reasonable expense. However, a 1.5-percent power factor in pressboard means the transformer power factor will be considerably less than 1.5 percent, for the power factor of oil is very low, and the dielectric constant of oil is also much lower than (about half) that of pressboard. So far no data is available that relates residual-moisture content to the expense of achieving it; 0.8-percent power factor in the large transformers (which probably represents 1 to 1.5 percent power factor in the pressboard) is feasible. It is not clear that equivalent results can be attained at reasonable expense on smaller transformers.

Many transformer designers do not agree that extremely low moisture content really adds to transformer life, and point out that practically no transformer failures have been traced to loss of tensile strength in the insulation. Furthermore, designers are all troubled by the practical difficulty of purifying insulating materials sufficiently that something besides moisture does not cause high power factor.

It should be kept in mind that during the loss of tensile strength the dielectric strength is maintained at practically full value, and that operating stresses (including impulse stresses) are usually well below insulation puncture strength.

Thus many transformer designers fail to see any one major virtue in extremely low-power-factor insulation. Of course, designers generally learn to take advantage of the slightly higher strength available from dry insulation, and take what advantage they can of the slightly lower dielectric constant of dry insulations. As their techniques for drying and preserving insulation improve, they will naturally tend toward designs with slightly higher stresses. Low-power-factor insulation eventually will mean that the user will have to be more careful to maintain it in a dry condition.

Inasmuch as it is fairly clear that extremely low power factor is of little value in a new transformer, consider the aspect of maintenance. Suppose the user hopes to detect entrance of moisture in service by measuring power factor. Is the effect of moisture on power factor more pronounced if the power factor was low to begin with than if it was high? According to previous investigations, the power factor increases rapidly with the percent moisture only when the per-unit moisture exceeds two percent by weight, so extreme dryness initially is of no advantage in detecting additional moisture. For example, one-percent moisture added to pressboard will

TABLE I—RELATIONS BETWEEN MOISTURE, POWER FACTOR, AND DIELECTRIC STRENGTH OF OIL-INSULATED PRESSBOARD[9]

Moisture (Percent)	Power Factor (Percent)	Dielectric Strength	
		1 Minute 60 Cycles	Impulse
1.2	1	51	230
2.25	2	50	200
2.7	5	49	180

raise the power factor from 0.9 to 1.2 percent, but an additional one-percent moisture will raise the power factor to over nine percent.

But suppose the initial power factor were high due to some factor other than moisture. What then is the effect of additional moisture on the power factor? This question has many possible answers, but it seems most probable that some contaminants that increase power factor will also obscure the effect of additional moisture, and will help to defeat the effectiveness of any program for detecting entrance of moisture by power-factor measurement. Then, too, if one or more contaminants are present that can raise the power factor, the manufacturer will probably have more difficulty determining by power-factor measurement whether he has dried the insulation satisfactorily. As it is not practical, especially on small high-production items, to make continuous megger readings to follow the drying by insulation resistance, power-factor measurements are the best check on proper drying. However, they are a reliable guide only if the manufacturer has purified the design to use only low-power-factor insulating materials and has used no materials that can possibly dissolve into the oil and cause increases in power factor.

This reasoning is the most effective justification for the desirability of low power factor of finished transformer-insulation structures. As has been shown, there are many reasons why high-power-factor insulation is perfectly suitable for service in transformers and no one can prove that transformer insulation must have any particular value of power factor to give good service for an indefinite time. But if insulation power factor is initially high because of contaminants other than moisture, detection of moisture by power-factor measurement becomes a poor and uncertain tool for either the manufacturer or the user. Clearly, elimination of all high-power-factor material provides a convenient tool for checking dryness at the factory and moisture entrance in the field.

All of this applies particularly to sealed transformers. Many dry-type transformers with organic insulation (cloth, paper) are protected from the atmosphere only by varnish or other treatment of the coils. Such coverings are not effective moisture barriers and permit absorption of a great deal of moisture in terms of what is necessary to cause large increases in power factor. Some varnishes delay absorption longer than others, and heavier and more numerous coats are effective in delaying absorption. Nevertheless, moisture penetrates any coating in a matter of days if the transformers are in a humid location, and in sufficient quantity to raise the power factor. For this reason dry-type organic insulation is always lightly stressed, so that the resulting dielectric loss is negligible. Low power factor of the insulation in these dry-type transformers cannot generally be expected, and usually is not maintained under humid conditions. Fortunately the moisture can come out as easily as it goes in, and usually the normal temperature of operation keeps the transformer fairly dry. Fortunately also, the voltage at which corona discharges form around dry-type transformers is usually somewhat reduced when the transformer is humidified.

An Engineering Personality

One of the standard beginnings of a biographical sketch for a successful engineer is to mention his particular childhood zeal for tinkering with alarm clocks and such. In the case of *Clarence Lynn* this is by all odds the best way to begin. His activities when growing up in a small Kansas town so far exceeded the common boyish curiosity in things mechanical that it foreshadowed his career of technical accomplishment. In it lies an understanding of Clarence Lynn.

When asked to reminisce, Lynn starts by saying, "I can't remember back far enough to recall when I wasn't building something." Not content with the usual kites, Lynn and a younger brother built two- and three-stage kites for extra altitude, made hot-air balloons and a furnace on wheels to fill them, and floated kittens to earth in parachutes attached to large kites. By 1908 he had built the family a phonograph, a wireless set, a battery-operated electric alarm clock from a discarded spring-wound clock, an electric-spark ignition system for lighting gas lights in the house—to mention a few. Only seven years after Kitty Hawk, he constructed—and flew—a 16-foot glider.

Kansas born, Lynn was Kansas educated. At the University of Kansas he characteristically compressed five years of electrical engineering and elected studies in four years, meanwhile earning

The dry-type power transformer insulated with glass, mica, and porcelain is much more resistant to moisture because these materials are practically impervious to it. It is doubtful that moisture content or insulation power factor have any related significance in these transformers.

Considering, then, that a purified transformer is the only one in which power factor of insulation indicates moisture content, it is clear that the cost of purifying the insulation must be balanced against the advantages of low power factor, which are: (1) possible longer life of insulation; (2) possible increased and more reliable sensitivity to moisture. The cost of purifying insulation is not negligible because of the existence of a large number of harmless materials, a minute quantity of which raise the power factor.

Many bonding materials, enamels, cements, varnishes, and die lubricants seem to contain small amounts of such materials—"seem to contain" because their behavior is not entirely uniform. Generally, it is difficult to count on low power factor if appreciable quantities of any such materials are used. Yet these materials are known to have no bad effect in actual service, and are often a practical necessity, especially in small coils. The need for low power factor is not so important that these materials must be eliminated.

In large power transformers bonding materials can be reduced to a negligible minimum, and previous investigations show that the power factor can be maintained at a very low value. It does not follow that small transformers can be manufactured economically in as pure a state. Experience shows that their power factor, initially "high," can increase still further without any moisture entering the transformer and without damage to the transformer.

If purified distribution transformers, in which power factor indicates moisture, are worth a real premium in cost to the users of such small transformers, they will undoubtedly be produced. The cost of "pure" materials is not necessarily high, but at present they are not generally available and the effects of all the possible contaminants are not well understood. Effectively this means that present cost is high. It is not yet clear that they would be able to command a higher price; thus such materials are not generally available.

REFERENCES

1—"The Basis for the Non-Destructive Testing of Insulation," R. F. Field, *AIEE Trans.*, Vol. 60, 1941, p. 890.

2—"Field Power Factor Testing of Transf. Insulation and Operating Experience," E. W. Whitmer, *AIEE Trans.*, Vol. 60, 1941, p. 605.

3—"Power Factor Testing of Transformer Insulation," J. B. Hodtum, *AIEE Trans.*, Vol. 60, 1941, p. 28.

4—"Bushing and Associated Insulation Testing by the Power Factor Method," Baltzly, Schlottere, *AIEE Trans.*, 1941, p. 308.

5—"The A-C Dielectric Loss and Power Factor Method of Field Investigation of Electrical Insulation," Doble, *AIEE Trans.*, 1941, p. 934.

6—"Factors Affecting the Mechanical Deterioration of Cellulose Insulation," F. M. Clark, *AIEE Trans.*, Vol. 61, 1942, p. 742.

7—"Effect of Dissolved Moisture on Dielectric Strength of Insulating Liquids," F. M. Clark, *AIEE Trans.*, Vol. 59, 1940, Page 433.

8—"Fundamentals of Electrical Insulation," J. Swiss, T. W. Dakin, Westinghouse ENGINEER, May, 1954, p. 114.

9—"Dielectric Measurements on New Power Transformer Insulation," W. L. Teague, J. H. McWhirter, *AIEE Transactions*, 1952.

CLARENCE LYNN

most of his way. He graduated in 1918 in time to spend nine months overseas in the "war to end war" as a Lieutenant.

While in school Lynn had spent one summer working at Westinghouse, where large rotating machines had an immediate fascination for him. The war over, he decided to make a career of it at Westinghouse. First came engineering design school under the incomparable B. G. Lamme. That over, he took off like a homing pigeon for the Power Engineering Department. He had in mind working on a-c machines. But there were no immediate openings in that department. Would a job in d-c machinery do? Sure, just so long as the equipment rotated.

Thus began a long career of accomplishment in the field of large d-c motors and generators. For years he was the acknowledged leader in the design of high-speed, high-capacity, d-c generators, motors, and direct-connected exciters. Some of his d-c machines operated at speeds up to 12 000 rpm. He was largely responsible for such important developments as the present use of laminated frames in large generators and motors for large reversing steel-mill drives, to improve commutation under transient-load conditions; was instrumental in the development of the first silicone-insulated, submarine propulsion motor; developed a line of extremely long-core, d-c motors of low inertia for steel mills; and has 25 patents covering d-c machinery, controls, and heat-treating furnaces.

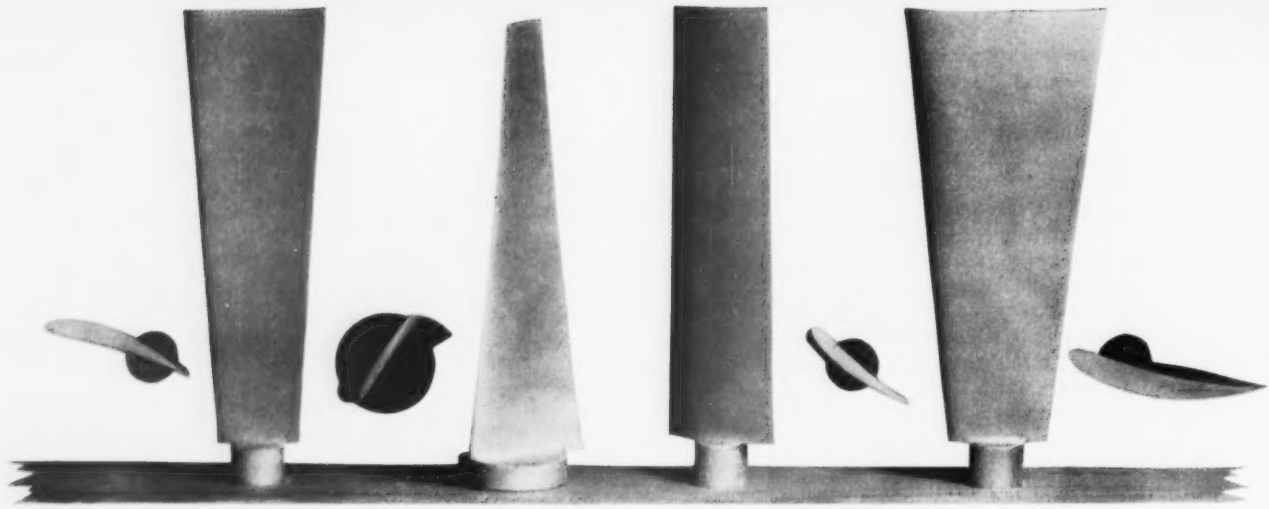
Before his management duties demanded a major portion of his time, Lynn was associated with graduate student educational work of Westinghouse, teaching in both engineering and design schools. In that line of endeavor, as well as in everyday technical contacts, he stresses getting and understanding a physical conception of the problem before attempting to solve it.

Advancement came regularly, and with it responsibility for many non-rotating equipments. By 1938, he was manager of the department that produced not only large d-c machinery but also induction voltage regulators, electric and fuel-fired furnaces and atmospheric gas generators.

In 1950 came the first major change in his engineering career. He was appointed Engineering Manager of the Atomic Power Division, then engaged in designing and building the first of two submarine-type nuclear-power plants. There, his experience, knowledge, and analytical ability, not only in electrical engineering but in mechanical and thermodynamic fields, found wide application. Since June, 1952, he has been at the Motor and Control Division at Buffalo as Executive Assistant to the Vice President. There his large fund of engineering experience is brought to bear on all sorts of problems.

A full-time job of engineering and directing the work of other engineers does not satisfy his passion for making things. It carries over into his spare time. He built his own automobile in 1922. And he proved that the "Lynn Special"—with an overhead-valve engine, and complete with nameplate and state registration—would run, at speeds of 75 mph. After which he promptly lost interest in it. He became a home-movie expert long before that genus of hobbyist became extant. Failure of central-station power due to lightning or storms will not put the Lynn home in darkness. In such an outage, a 2500-watt engine-driven power plant in his basement takes over.

Lynn is a man who must be busy—busy building things. It is his vocation; it is his avocation. He is a man in a hurry, of restless energy, of prompt decision. He is strictly honest in all engineering matters. For him to make an unrealistic commitment for expediency reasons is unthinkable. But that doesn't mean he is overconservative in engineering design. Lynn has always followed one precept, which in his own words is: "You learn from your troubles. To determine the limits of materials and designs you must build experimentally, not just as far as you know is safe—but beyond it, with of course care and caution." CAS



Developments in Axial-Flow Compressors

The idea of compressing gases in a machine in which flow is parallel to the axis of rotation is over a half century old. But present work on the axial-flow compressor is producing remarkable results.

A. I. Ponomareff, *Manager, Condenser Engineering, Steam Division, Westinghouse Electric Corporation, South Philadelphia, Pa.*

The ever-increasing demand for large volumetric flows of air at elevated pressures for large wind tunnels and gas-turbine power plants for industrial, marine, and aviation applications has resulted in spectacular advances in the development of axial-flow compressors.

Principles of the Axial-Flow Compressor

In an axial-flow compressor, air flows in an axial direction through an annulus, concentric with the axis of rotation of the compressor. The flow path of a multistage compressor decreases in area in the direction of flow to correspond to the diminishing air volume as the compression progresses from stage to stage. An axial-flow compressor stage consists of a rotating and a stationary row of blades. The two rows are spaced close together to reduce the axial length of the compressor. In each stage, the air velocity is first accelerated and then decelerated with an accompanying pressure rise through conversion of the velocity energy into static pressure (i.e., diffusion). This process of air acceleration and diffusion is accompanied by the deflection of air in each stage through a small angle in the direction of compressor rotation. The change in the tangential component of air velocity (i.e., parallel to the plane of rotation) is proportional to the change in momentum per pound of air. The product of the change in tangential component multiplied by the blade speed is, therefore, the work input per pound of air and is approximately proportional to the pressure rise. It is desired to have the rotor of each stage change the direction of the air as much as compatible with stability inasmuch as this is the only way to impart energy to the air stream in a compressor of given speed. While the increase in energy always takes place in the rotating row, the pressure increase through diffusion may occur in the blade passages of both the rotating and stationary blading rows.

Above—**Fig. 1 shows the actual blading designed to the velocity diagrams shown in Fig. 2.** *Left to right:* **examples of an inlet guide vane, a rotating blade, a stationary blade, and an outlet guide vane.**

The distribution of the pressure rise between the rotating and stationary rows of an axial-flow compressor is usually identified by *degree of reaction*. The degree of reaction may vary from zero to some 115 percent. The percentage of reaction indicates the percent of the total pressure rise in a stage accomplished in the rotating row of blades. "Fifty-percent reaction," for instance, indicates that the pressure rise in the stage is equally divided between the rotor and stator blades, while "90-percent reaction" means that all but 10 percent of the pressure rise is developed in the rotating blades. In a 115-percent reaction stage, 15 percent of the total pressure generated in the rotating row of blades is lost through pressure drop in the stationary row of blades.

A compressor stage with blading arranged for 50-percent reaction is well known as the *symmetric stage*. In this stage, the stationary blades are constructed as a mirror image of the rotating blades. It has been demonstrated that, theoretically, this is the most efficient compressor stage. The maximum efficiency of the 50-percent reaction stage may be some 3 percent higher than that attainable, for instance, with a 100-percent reaction stage. This is due primarily to the similarity between stationary and rotating blades, which permits their simultaneous operation at peak efficiencies. It is extremely difficult, however, to realize the above advantages in practice, due to the losses associated with high blade speeds, high velocities, and an extremely complex flow pattern

of the symmetric compressor stage. It is claimed that the stationary blade row of a compressor stage designed for reaction in excess of 100 percent contributes to the stability of flow (through pressure drop) and reduces the magnitude of unavoidable losses due to mismatching of compressor stages. The simplicity and stability of flow in a high-reaction compressor stage make possible accurate performance prediction.

Until a few years ago some compressors were built with a constant degree of reaction throughout the entire length of a machine. Thus a compressor could be identified as, say, a 75-percent reaction machine. In present compressors the degree of reaction may vary from stage to stage. Or, by use of warped blades, the degree of reaction at the base of a blade may differ considerably from that in the midsection or at the tip of the blade.

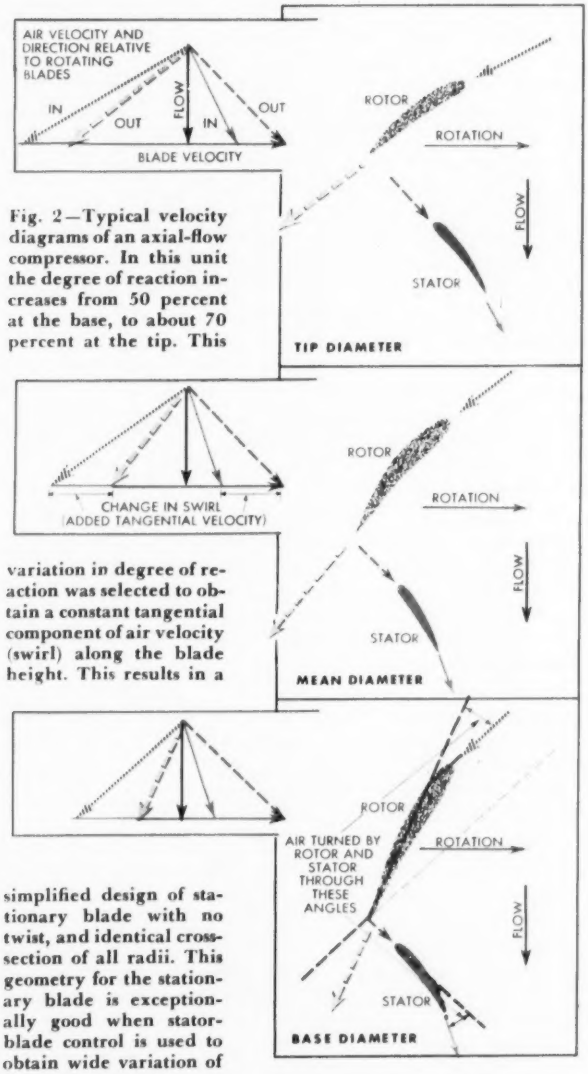


Fig. 2—Typical velocity diagrams of an axial-flow compressor. In this unit the degree of reaction increases from 50 percent at the base, to about 70 percent at the tip. This variation in degree of reaction was selected to obtain a constant tangential component of air velocity (swirl) along the blade height. This results in a simplified design of stationary blade with no twist, and identical cross-section of all radii. This geometry for the stationary blade is exceptionally good when stator-blade control is used to obtain wide variation of flow at a constant compressor speed. Each velocity diagram, to the left of its respective blade section, is combined from the vectors indicated on the blade cross-sections at the right. In the velocity diagrams the length of vectors indicates velocity and angle represents direction. On the diagrams of blade cross-section, in the interest of clarity, the vectors show angle only; the lengths of the vectors are not to scale.

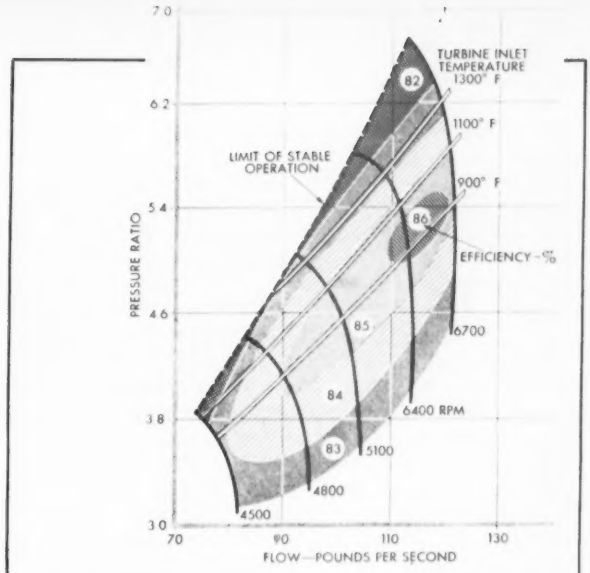


Fig. 3—Characteristic curves of the axial-flow compressor of a 5000-kw gas turbine. Superimposed on the curves of pressure-ratio versus flow are the curves representing conditions set by three operating temperatures, and resulting efficiencies for this particular machine. These curves show, for example, that with a turbine inlet temperature of 1300 degrees and a constant speed of 5000 rpm, the limit of stability is reached with a flow of about 90 pounds of air per second, at which condition the pressure ratio is about 4.8 and the efficiency is about 83 per cent. Or, for example, with the machine operating at turbine inlet temperature of 1100 degrees and a speed of 5100 rpm, the pressure ratio is about 4.8; the flow 97 pounds; and the efficiency, 85 percent. A pressure ratio of, say, 5.4 at the same inlet temperature could be achieved with this machine only by raising the speed to nearly 6400 rpm. A flow of 112 pounds would result and the efficiency would not change appreciably.

Velocity Diagrams

The three-dimensional flow pattern through an axial-flow compressor can be represented by three components of the absolute air velocity, namely: axial, tangential (swirl), and radial. Of these three, the radial-velocity component is the smallest, and is usually disregarded in compressor design, thus resolving the problem to the treatment of two-dimensional flow. The components of the absolute air velocity, blade speed, and relative velocity, when combined vectorially, become what is known as velocity diagrams; often called velocity triangles.

Velocity diagrams are used in the design of an axial-flow compressor stage to establish the blade geometry needed for a desired pressure rise at a given speed. In a modern, well-designed compressor stage, velocity triangles vary with the radius in accordance with the assigned distribution of the energy input along the radial height of the blade, i.e., with the degree of reaction. For optimum design, the proper relationship must be maintained between the axial and tangential components of air velocity and the energy input at various radii, in order to satisfy the conditions of radial equilibrium and so minimize undesirable secondary flows.

Typical velocity diagrams of an axial-flow compressor stage are shown in Fig. 2 and the actual blading designed to achieve these diagrams is shown in the photograph at the top of page 218.

Compressor Performance

The performance of an axial-flow compressor is usually represented by so-called characteristic curves (Fig. 3) of the pressure ratio and efficiency versus the flow in cubic feet per minute or pounds per second for various operating speeds. The operating range of an axial-flow compressor is somewhat limited by surge or stall characteristics. When the flow through an axial-flow compressor operating at a given speed is reduced to below about 90 percent of rated flow, through an added resistance due to accumulation of dirt or an obstruction in the ducting, surges in discharge pressure develop. These are accompanied by a large increase in noise and mechanical vibration. The pressure surges are usually mild at low compressor speeds, but attain violent proportions at higher speeds, endangering the compressor. This limit of stable operation sometimes is referred to as the *surge line*, *stall line*, or *pumping limit*.

The performance of an axial-flow compressor blade row is similar to that of an airfoil, such as the wing of an airplane. The pressure rise across the blade row of an axial compressor is related to the lift produced by an individual airfoil or airfoil grid (i.e., the configuration resulting from forming blades into a row). The relation of the compressor-stage performance (pressure rise), lift characteristics of an isolated airfoil, and the flow pattern around the compressor blade section are shown in Fig. 4.

To impart the maximum amount of energy to the air, it is desirable to turn it through as large an angle as possible. However, there are limits to which this can be done. At the design condition *A*, the blades in the compressor row are operating at a favorable angle of attack to produce a certain lift, with resultant pressure rise at a given air velocity. The flow pattern shows the proper relation of the inlet and outlet air velocities with respect to the blade section with no flow separation at any point. With the increase of the angle of attack through the reduction of flow, the lift is increased up to a maximum value, shown at *B*. The pressure rise generated is at the maximum. The flow pattern shows a slight separation at the trailing edge of the airfoil section, which indicates an incipient stall. A further increase in the angle of attack results in decrease in lift, as shown at *C*, with the corresponding drop in pressure rise. This is the stall or surge condition. The flow pattern shows a definite separation of flow from the airfoil section and the flow is generally unstable, exhibiting pulsation in pressure and noise intensity. It is the result of attempting to turn the air through too large an angle.

Axial-Flow Compressor Applications

The axial-flow compressor is inherently a high-flow, high-speed machine. The capacity for high volumetric flow at high-efficiency levels makes the axial-flow compressor extremely attractive for wind-tunnel and industrial gas-turbine power-plant applications. The small physical dimensions, light weight, and small frontal area associated with high speed have resulted in universal acceptance of the axial-flow compressor for aviation gas-turbine power plants.

Blast-Furnace Charging—The results of tests recently conducted as a joint undertaking by the United States Steel Corporation and Westinghouse at Carrie Furnace in the Homestead District Works have shown that blast-furnace gas can be successfully burned in high heat-release gas-turbine combustion chambers at a high efficiency. It is believed that blast-furnace gas will become another fuel for gas turbines and the axial-flow compressor will soon serve the steel industry for blast-furnace charging, and as a component of the gas-turbine power-generating units.

A gas-turbine power plant for burning blast-furnace gas, arranged for air extraction at a continuous rate in excess of 125 000 cfm, is being developed for a commercial application. In this unit, atmospheric air will be compressed by an axial-flow compressor to a pressure of approximately 3½ atmospheres. At the compressor discharge, a part of the air will be bled for blast-furnace gas blowing. Blast-furnace gas fuel, mixed with the remainder of the air, will be burned in the combustors and then expanded in the gas turbine to drive the blast-furnace and gas-fuel compressors.

Wind-Tunnel Application

The selection of the most suitable compressor for a large wind tunnel requires careful consideration, in view of large power consumption and the necessity of matching of compressor performance to wind-tunnel requirements.

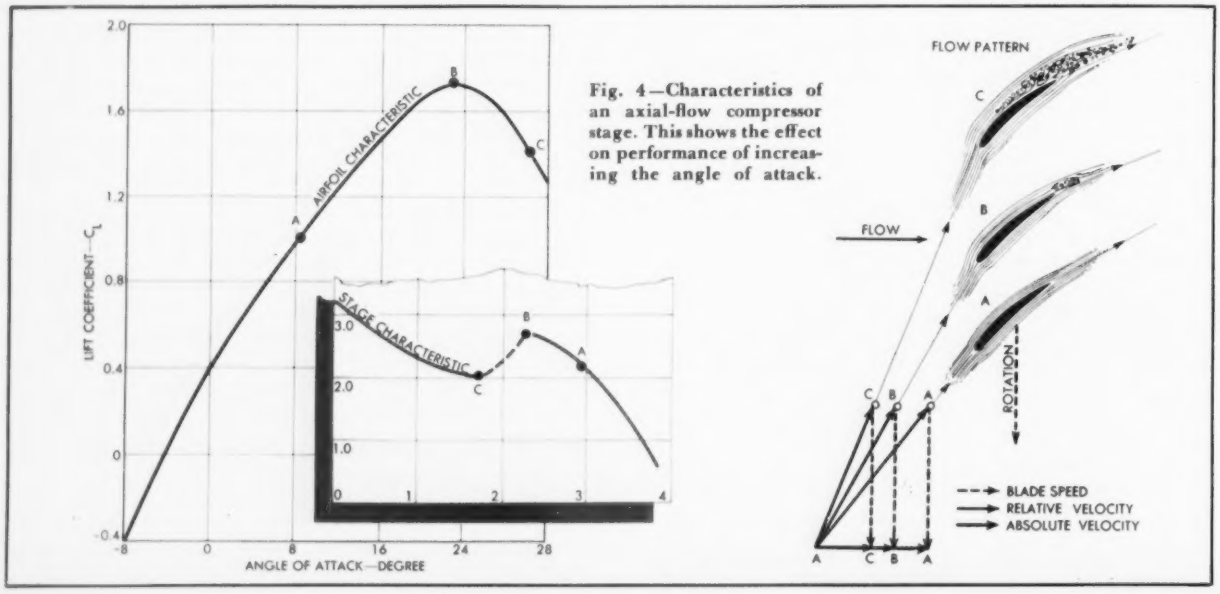


Fig. 4—Characteristics of an axial-flow compressor stage. This shows the effect on performance of increasing the angle of attack.

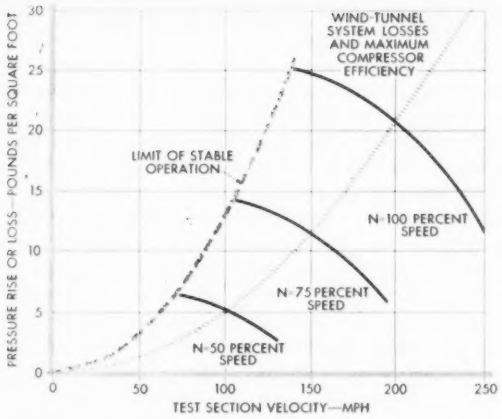


Fig. 5—Performance of a compressor for a low-speed tunnel.

Subsonic Wind Tunnels—In a low-speed subsonic wind tunnel operating at Mach numbers up to 0.8 (approximately 610 miles per hour air speed in the test section), the pressure drop through the tunnel circuit is essentially a friction loss. This loss is proportional to the square of the air velocity in the test section, while the volume flow is directly proportional to the test-section air velocity. Since the compressor characteristics are such that the total pressure rise is approximately proportional to the square of the compressor speed, and the capacity or the volume flow is directly proportional to the speed, operating requirements of subsonic wind tunnels are adequately met by a variable-speed compressor. Many low-speed wind tunnels successfully use a variable-speed motor control to cover the entire range of tunnel air velocities.

The characteristics of pressure rise versus flow of a variable-speed compressor superimposed on the subsonic wind-tunnel system losses are given in Fig. 5.

Transonic and Supersonic Wind Tunnel—In high-speed transonic and supersonic wind tunnels designed for operation at Mach numbers above 0.8, the above criterion of the tunnel performance does not apply, due to large effects of high Mach number on flow through the tunnel circuit. The disturbances caused by a body present in the field of moving fluid are propagated throughout the fluid by pressure waves moving with the velocity of sound. In subsonic flow (velocities below that of sound), the flow can adjust itself gradually for whatever flow conditions exist upstream. The losses associated with subsonic flow are a function of the fluid velocity, density, and viscosity (Reynold's numbers). In supersonic flow (velocities above the speed of sound), the gradual adjustment of flow to the geometry that lies downstream is not possible, and a sudden discontinuity in flow takes place, accompanied by the formation of compression shock waves. The energy due to these shock waves is responsible for large pressure drops that have to be matched by the pressure rise through the compressor serving the tunnel. Furthermore, the flow through the supersonic wind-tunnel test section is no longer directly proportional to the air velocity through the compressor, since the flow is effectively controlled by the critical velocity through the nozzle-throat geometry of a tunnel. Accordingly, the pressure drop in a supersonic wind-tunnel circuit is a function of the test-section Mach number, rather than a function of air velocity in the test section.

The above characteristics of the supersonic wind-tunnel system require an extremely wide variation in the pressure losses (pressure ratio) at a substantially constant volumetric flow. Such requirements cannot be effectively covered by a variable-speed compressor with typical characteristic curves as shown in Fig. 5.

The transonic and supersonic wind-tunnel requirements for an extremely wide range of pressure ratios can be met with various degrees of effectiveness by one or a combination of the following: (1) use of a multiple-compressor unit; (2) use of air-bypass arrangement; (3) adjustment or control of compressor rotor-blade orientation; and (4) adjustment or control of compressor stator-blade orientation.

It is possible to cover a wide range of flow and pressure ratios with a large number of compressors arranged for parallel and series operation. Detailed evaluation, however, usually reveals many disadvantages of such a system. Multiple compressors unduly complicate the electrical and aerodynamic control, increase the starting time, require a larger space for the installation, and involve high maintenance. Use of air bypass for extension of the flow range involves a large loss of power and should be considered only in conjunction with multiple compressors. Use of adjustable rotor blades to obtain optimum operating performance has been successful for hydraulic turbines, aircraft propellers, and for some wind-tunnel installations. It has been demonstrated that an axial-flow compressor designed to permit adjustment in the orientation of the rotating blades usually provides sufficient flexibility in volume flow to meet the operating requirements of a supersonic wind tunnel. However, for large wind tunnels, the compressor rotor blades are subjected to enormous aerodynamic and centrifugal loading as well as to vibration due to various air disturbances present in the wind-tunnel circuit.

Compressor Performance with Stator-Blade Control—The complexity of mechanical design problems of rotor blades, especially when the adjustment of blade orientation is to be made while the compressor is in operation, leads to serious consideration of stator-blade adjustment. Recent developments on axial-flow compressors have indicated that the control of stator-blade orientation is likely to prove to be the most practical way to provide for a wide variation of flow while operating at a constant speed. Tests of an axial-flow compressor model indicated that the adjustable stator-blade design can provide a range of volume flow of nearly two to one with the compressor efficiency level above 80 percent. The performance of a typical compressor designed for stator blade control at constant operating speed is shown in Fig. 6.

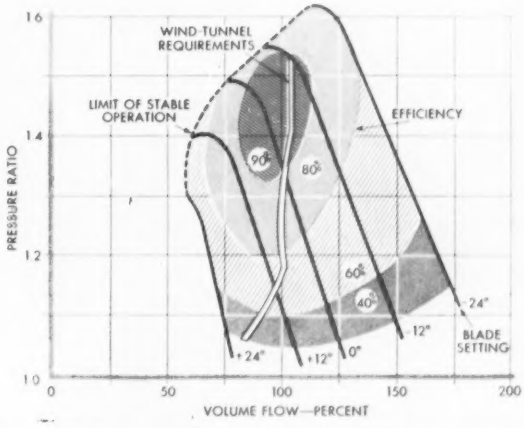


Fig. 6—Performance of a compressor for a high-speed tunnel.

Other Applications

Use of axial-flow compressors for other commercial applications at present is somewhat retarded due to high manufacturing cost associated with the close tolerances and the quality control required for construction of a high-speed machine. The cost of compressor blades manufactured to rigid dimensional specification, for instance, is responsible for some 40 percent of the total manufacturing cost of an axial-flow compressor. Accordingly, much of the present development on axial-flow compressors is directed toward the reduction of the manufacturing cost through the application of more efficient blade manufacture and by a reduction in the number of stages required for a given pressure ratio.

Subsonic, Transonic, and Supersonic Compressors

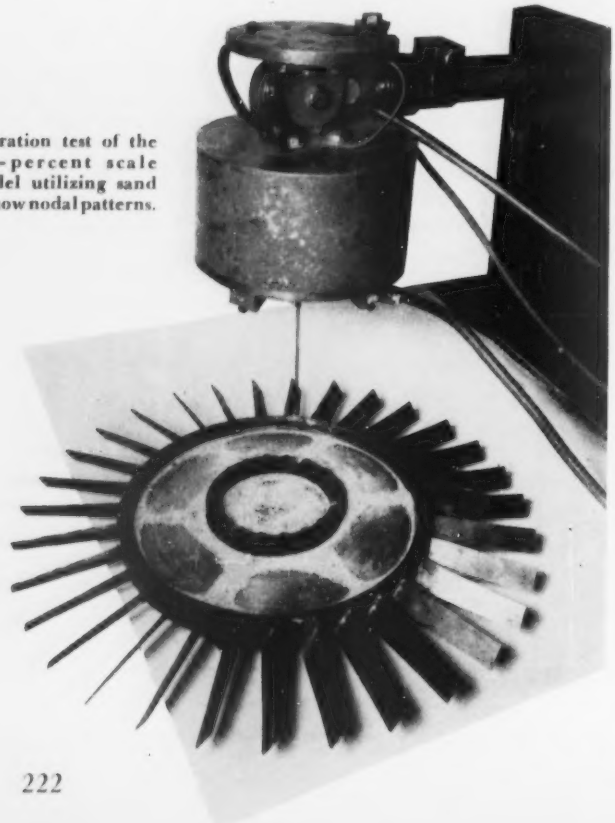
The pressure rise in an axial-flow compressor stage is a function of the change in the tangential component of air velocity and of the blade speed. To increase the pressure-generating capacity of the compressor stage, the magnitude of one or both of these factors must be increased. An increase in the change of tangential or swirl component requires proper selection of blade geometry, axial velocity, and incidence angles to effect the increase in blade turning at high efficiency. Data from cascade tests indicate that blade turning cannot be increased with the available blade sections beyond the present limits without serious effect on efficiency and with a reasonable margin from stall.

Much new information was gained during the last few years toward a better understanding of flow phenomenon and operating stresses in the axial-flow compressor, through the application of strain gauges and various pressure pickups. While from a stress standpoint the additional knowledge does permit operation of compressors at higher speeds, the corresponding increase in the pressure-generating capacity of a compressor stage designed for subsonic flow is subject to severe limitations due to Mach-number effect. Mach-number effect manifests itself in reduction in compressor efficiency due to the formation of compression waves in the blade passages when the local air velocities reach sonic levels. With the accepted definition of Mach number as the ratio of the relative air velocity at the compressor stage inlet to the velocity of sound, the local sonic velocity in the blade passages may be reached with the average Mach number as low as 0.7.

The detrimental effects of Mach number on compressor performance due to high local velocities can be minimized through proper adjustment of compressor-blade geometry. In a so-called transonic-compressor stage, the blade sections are designed with a sharp leading edge and the blade thickness ratio is distributed in such a way as to avoid the local increase

Vibration-Safe Transonic Compressor

The giant compressors for the Tullahoma wind tunnel had to be designed first of all to do the job. No less important is that they not wreck themselves due to resonance vibrations.



Vibration test of the 7½-percent scale model utilizing sand to show nodal patterns.

VIBRATION must be considered in turbine and compressor design, as it is the cause of most blade and disc failures. Each revolution the blades are subjected to a variable bending load because the struts, corners, etc., create variation of flow around the circumference. If this fluctuating load is in resonance with a natural frequency of the blades or discs to which they are attached, its effect is greatly magnified and can lead to fatigue failures.

When the natural frequency is high enough that a blade has a frequency of vibration greater than about six cycles per revolution, the natural damping of the 12-percent chrome steel limits the amount of buildup due to resonance. The blades can generally be made strong enough to withstand this vibration without fatigue failures. When the natural frequency is low, however, the input of vibratory energy is larger, and it is not practical to make the blades strong enough to withstand resonant vibrations. The solution is then to "detune" the system, i.e., to design the blades and discs such that no natural frequencies coincide with a low multiple of the rotating speed.

To detune successfully, the natural frequencies of the rotor structure must be predicted. Various methods for calculating natural frequencies of blades mounted on a rigid rotor are known. Methods of calculating disc frequencies are also available. However, the rotor for the transonic compressor at Tullahoma is both complex and extremely large.* It is composed of three bladed discs separated by spacers all held to

*A description of the compressor construction is given in "Mechanical Aspects of the PWT Compressor," by George H. Heiser, *Westinghouse* ENGINEER, July, 1954, p. 152–6.

of relative air velocity to sonic until the average Mach number approaches 1.0. From mechanical-strength considerations, conventional laminar-flow airfoil sections are used where the local velocities are low. It has been demonstrated that such a transonic compressor stage can produce a pressure ratio in excess of 1.3 per stage at an acceptable efficiency level. The comparison of the effects of Mach number on compressor efficiency for the subsonic and transonic compressor stages is shown in Fig. 7. In a multistage axial-flow compressor, the last stages operate at considerably higher air temperature with correspondingly lower Mach numbers. Accordingly, the last compressor stages are not adversely affected by Mach number and the use of transonic stages may be limited to the first two or three stages.

In an effort to generate still higher pressure ratio in an axial-flow compressor stage, various types of supersonic stages have been tried experimentally. In the supersonic-compressor stage, blades are shaped to produce compression shock waves in the passages of the rotating or stationary blades. A large and sudden change from supersonic to subsonic velocities takes place across a shock wave. The efforts of designers of supersonic compressors are directed toward the recovery of the energy in the shock waves through efficient diffusion of velocity into static pressure. The supersonic compressor-stage design presents extremely complex flow problems associated with extremely sudden changes of velocities, say, from Mach number 1.5 to 0.8 across the shock wave. The basic requirement for an extremely thin blade section for supersonic flow and proper control of shock waves and enormous dynamic forces acting on blades present complicated problems requiring solution before commercial application.

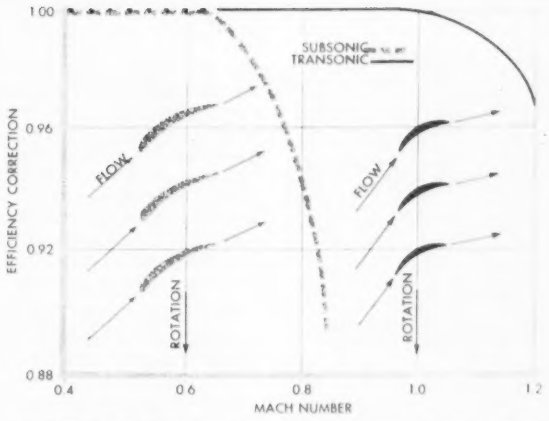


Fig. 7—Effect of Mach number on subsonic and transonic stages.

–via models

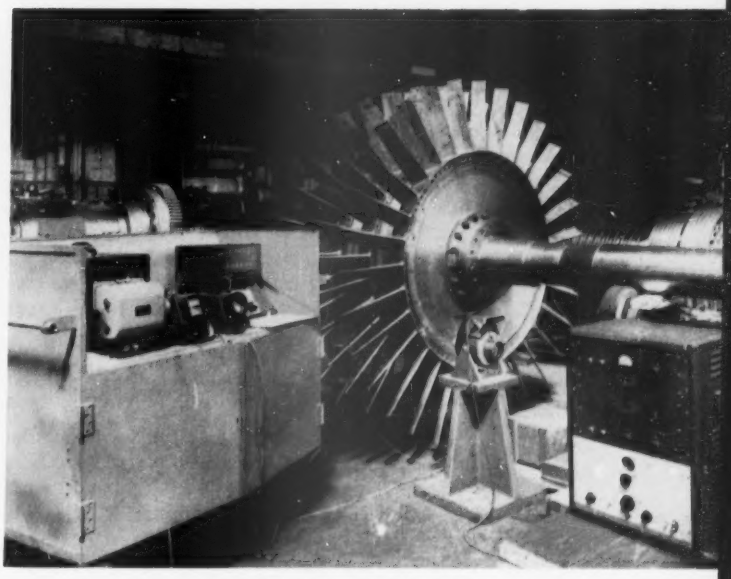
D. D. ROSARD, *Mechanical Design Section, Steam Division, Westinghouse Electric Corporation, South Philadelphia, Pa.*

stub-shaft ends by long bolts. For such a massive construction the calculation of the vibration characteristics of the combined disc-blade system became extremely time consuming, particularly because of the outer spacers. By the use of an IBM Card Programmed Calculator, it was possible to do the required calculations in reasonable time.

At the same time, an extensive program of model tests was undertaken. A 7½-percent model was used for preliminary studies, such as determination of optimum diameter of outer spacers and effect of blade roots on vibration characteristics.

A quarter-scale model was then built and tested both statically and dynamically. In the stationary test, the discs were excited by an electromagnetic vibrator. At resonance, the vibrations took the form of an even number of pie-shaped segments, which alternated in moving up and down, while the "nodal" diameters remained still. The deflections along the circumference appeared approximately as sine waves, being equal to the number of nodal diameters.

In the rotating test, the model was rotated in a sealed enclosure evacuated to minimize windage losses. Excitation was provided by a stationary steam jet, and the resulting vibrations were measured with strain gauges through slip rings. As the speed was varied, the various modes of vibration were excited whenever their natural frequency was an exact multiple of the rotating speed. If the vibration frequency was n times the rotating speed, for instance, every blade as well as every point on the rim of the discs makes n full cycles of vibration during each revolution. There are n waves around the rim of the disc and therefore n nodal diameters. This vibration pattern remains stationary in space, providing a "track" that is followed by the spinning blades and discs. Natural frequencies of the quarter-scale model were four times the frequencies of the full-size compressor, therefore the model was



The quarter-scale model undergoing its static test.

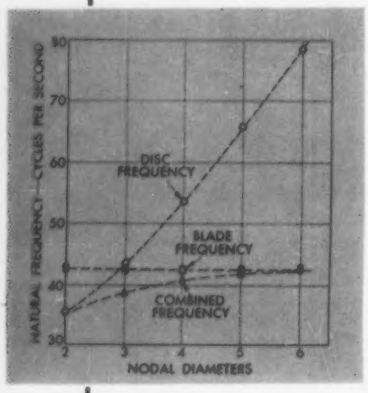
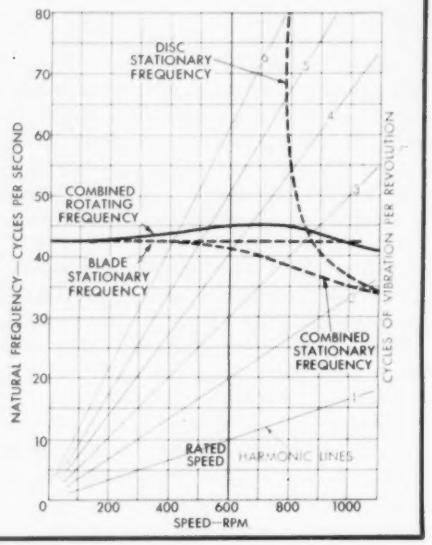


Fig. 1—Variation in natural frequency of discs and blades separately and combined, rotor stationary. Disc frequency is calculated frequency of disc vibrating in nodal diameter pattern, assuming blades to be perfectly rigid, and with restraints of outer spacers. Blade frequency is calculated frequency of a blade vibrating as a cantilever beam, assuming disc rigid. Combined frequency is natural frequency of the real combination of disc and blade calculated and tested.

Fig. 2—Variation of the natural frequencies of the blade and disc, separately and combined. The dotted lines give the relationship of frequencies of disc and blade alone and combined with respect to harmonic frequencies (see Fig. 1). The solid line gives the combined natural frequencies when rotating. This shows the stiffening effect of the centrifugal forces. At the rated running speed of 600 rpm, the natural frequency of the blade and disc system falls midway between the fourth and fifth harmonics.



run up to 2400 rpm (compressor operating speed is 600 rpm).

As the number of nodal diameters increases, the disc frequency also increases as shown in Fig. 1. Obviously, the blade frequency as defined above is a constant for all nodal diameters. The combined frequencies approach the disc frequencies at low numbers of nodal diameters, and approach the blade frequency at high numbers of nodal diameters. At the point where the separate disc and blade frequencies are equal, the combined frequency may be appreciably lower than either uncoupled frequency. These results are plotted in Fig. 2.

In designing the rotor structure to avoid resonant vibrations, the blade frequencies are controlled by adjusting the blade cross-sections, the disc frequencies are controlled by the varying disc thickness and adding outer spacers as required. Both blade and disc frequencies must be properly adjusted to result in a satisfactory combined diagram.

• • •

Engineering Notes

New Highs in Generating Equipment

Significant increases in efficiency, steam pressure, and temperature will be incorporated in power-generating equipment to be built for a new Philadelphia Electric Company station. The 275 000-kw turbine-generator unit—to be built by Westinghouse—is the largest yet ordered. The steam generator, to be built by Combustion Engineering, Inc., will supply steam to the turbine at the highest steam pressure and temperature of any in the world—5000 psi and 1200 degrees F—although initial operation will be at 1150 degrees.

The 3600-rpm tandem-compound turbine will utilize triple-flow exhaust to the condenser, and double reheat. Both reheats will be to 1050 degrees F.

The first, or super-pressure, turbine element will be designed for initial steam conditions of 5000 psi and 1200 degrees F, exhausting at about 2400 psi. Other turbine elements are of conventional design, using ferritic materials.

The generator will be rated at 352 000 kva, 3 phase, 60 cycles, 24 kv, 3600 rpm. Inner cooling will be used on rotor and stator conductors; hydrogen pressure will be 45 psi. Motor-driven d-c generators will provide excitation for the main generator. Magamps will regulate terminal voltage.

The boiler will be designed for maximum steam conditions of 6000 psi and 1200 degrees F. At rated load primary steam flow will be 1 540 000 pounds per hour.

Expected plant heat rate for steam conditions of 5000 psi and 1150 degrees F is 8400 Btu per kilowatthour, about 600 Btu less than the most efficient existing power station.

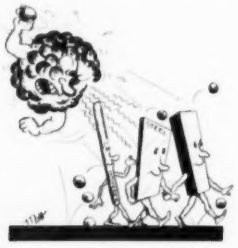
Recording Hysteresis Loops above 100 Kc

The magnetization loops of magnetic materials in the kilocycle and megacycle region are hard to come by. In fact, until lately there has been no really satisfactory routine way of getting them.

An all-electronic hysteresis-loop tracer draws on a screen the *B-H* curves of new magnetic materials at any frequency from 100 kc to several mc as readily as a 60-cycle loop. A toroidal core of the material is used. The core may be of ferrite (magnetic ceramics), or it may be wound from thin strips of metallic materials, which in some cases are as thin as $\frac{1}{8}$ mil. This kind of core is often used for applications such as magnetic amplifiers, transformers, computers, and other electronic gear. The core is given two windings. One is connected to the adjustable-frequency generator, and the current through the winding is representative of the magnetizing force. A voltage proportional to this current, and thus to the magnetizing force, is amplified electronically and presented to the x-axis of an oscilloscope. The output signal from the second winding is, after being integrated, proportional to the magnetic induction, and is likewise amplified to become the input to the y-axis of the scope.

Personality Profiles

William A. Johnson is an experienced hand in the relatively new field of materials for nuclear reactors. A Lehigh University graduate (1935) he earned his doctor of science degree from Carnegie Tech before coming to Westinghouse as a Research Fellow in 1939. He became a section manager at the laboratories in 1946, and shortly was loaned by Westinghouse to



organize a metallurgy division at the Oak Ridge National Laboratory. In 1948 he returned to the Company's Atomic Power Division as manager of the materials and metallurgy subdivision. Here he has had to contend with the many knotty problems concerning nuclear-reactor materials. He is now manager of the Materials Department.

• • •

Edward Beck is back again in this issue with his ninth article, and again it's on a phase of his specialty—this time lightning arresters. In case you've forgotten, Beck heads the Lightning Arrester Section.

• • •

It was only 11 years ago that *D. D. Rosard* and his family, living in southern France, eluded the invading Nazi and came to the United States via Spain. Rosard has crowded a lot of activities into this short time. Almost immediately on arriving in this country he entered Drexel Institute, obtaining his degree in mechanical engineering in 1947. To this he added an M.S. in E.E. from the University of Pennsylvania in 1953.

Since joining the Steam Division of Westinghouse in 1948, Rosard has worked in the Mechanical Design Section, the Thermodynamics Section, and did two years' work on steam-turbine control. Early in 1951, Westinghouse began work on the world's largest compressors for the Tullahoma wind tunnel, in which Rosard was to have an important hand in the analysis of stresses and vibration.

Although most of Rosard's time since early 1951 has been occupied with the Tullahoma compressor, he has also helped with the stress and vibration analysis of the new 25-inch exhaust row steam-turbine blade.

Like several of our authors this month, *E. C. Wentz* is a repeater. Previous articles have dealt with transformers, his field since he joined Westinghouse in 1926. A University of Minnesota graduate, he first went to work in the Instrument Transformer Section and became manager of that section in 1942. Recently, Wentz was made manager of the power-transformer development group that is concentrating on finding new and better equipment designs.

• • •

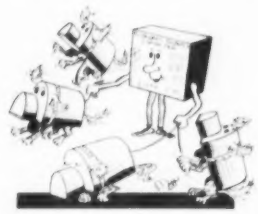
"In 1922 a young man still in his teens landed in San Francisco. By a devious route he had come from Russia, and was a veteran of the Russian war against Germany and of the more recent revolution. He spoke no English, had no money, knew no one. He got a job in the gold mines, then as a fruit picker, and attended YMCA classes in English. In 1923 he entered the University of Utah and 3½ years later graduated with a B.S. in M.E., having provided, as he went along, the funds for his education."

This paragraph, which headed the profile of *Alexander I. Ponomareff* on this page in March, 1947, reveals much of the man about whom it was written. Ambition, diligence, patience, and plain hard work are all characteristic of Ponomareff. And they have made him a recognized expert in his primary field of activity—axial-type blowers and compressors.

After he graduated, Ponomareff came to Westinghouse, and shortly he went to work on steam-turbine design and development. After about three years he left the Company, but returned to Westinghouse in 1932, and embarked on his present field of activity. He led the development of the commercial axial-flow blower, and has contributed innumerable ideas and much effort in the field of axial-flow compressors. Ponomareff is presently manager of the Condenser Engineering Section.

• • •

Extemporaneous speaking is an art. Certainly no less an art—but quite a different one—is to extemporaneously dictate a clear, concise article on a highly complex subject. *E. L. Harder* is quite adept at both. When we first discussed the possibility of the article on economic load dispatching (p. 194), we suggested Harder give us a general idea of the area he proposed to cover. There followed a 20-minute discourse on the subject that left us with essentially no questions to ask. Altering his style only slightly, Harder dictated the article over a weekend.



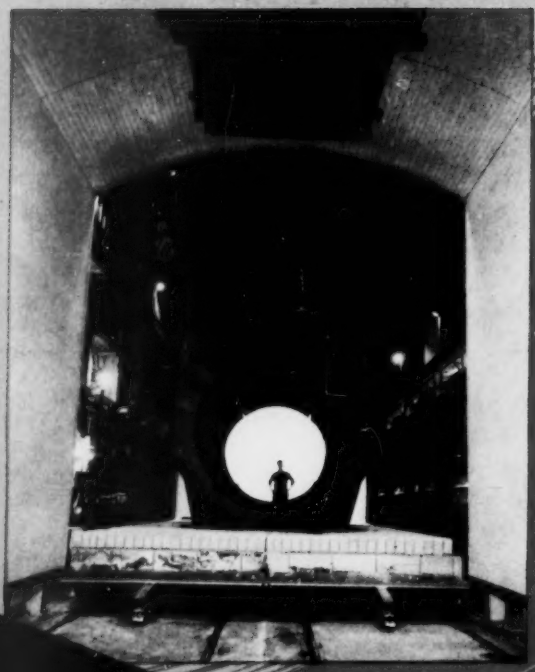
This ability to visualize clearly a complex or abstract problem stands Harder in good stead with his present position as Director of the Analytical Section in East Pittsburgh. Here he is in charge of a "fleet" of computers and calculators.

Harder, an electrical-engineering graduate of Cornell University, came to Westinghouse in 1926. After finishing the Graduate Student Course he became a central-station engineer. In 1946, he was appointed a consulting transmission engineer, in which job he had varied activity, among them early work on the analog computer. In between all this Harder found time to obtain his M.S. in 1931 and a Ph.D. in 1946.

• • •

The name *Samuel G. Hibben* will sound familiar to many of our readers. Undoubtedly a goodly percentage have either read his previous articles or perhaps heard one of his interesting and entertaining talks. The odds are almost prohibitive that his subject was on some phase of lamps or lighting, a field that he has been in since he was 14, and professionally associated with since 1910.

Hibben's career has been varied. After graduation from Case, he spent several years with the Macbeth Glass Company designing glassware, lenses, and reflectors. Then in 1916, after two years as a consulting engineer, Hibben came to Westinghouse as a lighting engineer. Since that time he has been associated with countless lamp and lighting developments, including street lighting, military searchlights, underwater floodlights, lighthouse beacons, illumination of monuments, tunnels, fairs and expositions, as well as home lighting. He now serves the Lamp Division as a consulting engineer.



This huge heat-treating furnace is used for stress relieving large weldments. The newly installed furnace has a usable charge space 30 feet long, 18 feet wide, and 16 feet high, and can hold a hundred tons of parts for treatment. In the photo below, a turbine-generator frame is being prepared for a three-day heat treatment. As can be seen, the front door of the furnace, as well as the floor, rolls out of the furnace—20 car wheels ride on four railroad-type tracks. The view at left is from the inside of the furnace, looking out. Stress relieving will be performed at about 1175 degrees F.